COMPUTER-ASSISTED PROCEDURES TO GENERATE AND EVALUATE REGIONAL HIGHWAY ALTERNATIVES

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A.K.F. TURNER

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PURDUE UNIVERSITY
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Final Report (Part I)

COMPUTER-ASSISTED PROCEDURES TO GENERATE AND EVALUATE REGIONAL HIGHWAY ALTERNATIVES

by

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Joint Highway Research Project
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Conducted by

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Purdue University

in cooperation with the

Indiana State Highway Commission

and the

U. S. Department of Transportation
Federal Highway Administration
Bureau of Public Roads

The opinions, findings and conclusions expressed in this publication are those of the authors and not necessarily those of the Bureau of Public Roads.

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Final Report (Part I)

COMPUTER-ASSISTED PROCEDURES TO GENERATE AND EVALUATE REGIONAL HIGHWAY ALTERNATIVES

To: J. F. McLaughlin, Director
Joint Highway Research Project

From: Harold L. Michael, Director
Joint Highway Research Project

December 18, 1968

File No. 1-6-1

Project No: C-36-72A

Attached is Part I of a Final Report on the research project "Evaluation of Numerical Surface Techniques Applied to Highway Location Analysis" which was approved on July 1, 1967. This report, entitled "Computer-Assisted Procedures to Generate and Evaluate Regional Highway Alternatives", has been authored by Mr. A. Keith F. Turner of our staff under the direction of Professor R. D. Miles. Further portions of the final report will be presented to the Board by June 1969 and will document the computer programs utilized in this study.

This report describes the Generalized Computer-Aided Route Selection (GCARS) System which has been developed by the author to improve regional highway planning procedures. Results of this new type of analysis are shown for two Indiana test areas.

The report is presented to the Board for review and comment and for the record.

Respectfully submitted,

Harold L. Michael
Associate Director

HLM:lc

Attachment

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TABLE OF CONTENTS

Page

LIST OF TABLES vi

LIST OF FIGURES vii

ABSTRACT xiii

CHAPTER I - INTRODUCTION 1

The Route Location Process 1
    The Role of Transportation 1
    Applications to Developing Regions 2
    The Hierarchical Structure of the Highway Location Process 4
    Present Highway Location Procedures 9
    The Need for Improvements 10
The Role of the Computer in Highway Engineering 12
    Computer-Aided Design Procedures 13
The Generalized Computer-Aided Route Selection (GCARS) System 15
Purpose of Study 19
Scope of Study 20

CHAPTER II - REVIEW OF PROPOSALS FOR IMPROVEMENTS IN HIGHWAY LOCATION AND DESIGN TECHNIQUES 22

Graphical Route Selection Procedures 22
Computer-Assisted Design Procedures 28
    Robert's 1957 Proposal 28
    The Digital Terrain Model 32
    The ROADS System 36
    The CARD System 39
    The TE.GI System 40
Computer-Generated Driver's-Eye Movies 42

CHAPTER III - REVIEW OF PROCEDURES TO BE EVALUATED 45

Numerical Surface Analysis Procedures 45
    Subjective Methods 47
    Semi-Objective Methods 48
    Objective Methods 50

Page

Vector Analysis Procedures 50
Power Spectrum Analysis Procedures 57
Surface Comparison Procedures 57
Regression Procedures 59
Trend Surface Analysis Techniques 63
Procedures for Trend Surface Description 64
Statistical Evaluation of Trend Surfaces 64
Procedures for Trend Surface Interpretation 71
Procedures for Description of Residuals 72
Procedures for Interpretation of Residuals 75
Computer-Generated Graphical Display Procedures 76
Display System Characteristics 77
Methods of Surface Representation 78
Benefits and Limitations of Machine-Generated Contour Maps 79
Minimum Path Analysis Procedures 80
The Theory of Graphs 80
Classification of Minimum Path Algorithms 83
Comparison of Alternative Minimum Path Algorithms . . . 85
Special Applications of Minimum Path Algorithms 87

CHAPTER IV - METHOD OF INVESTIGATION 91

Identification of Highway Location Factors 91
Factors Studied by the GCARS System 95
Selection and Description of Test Areas 96
Description of the Southern Test Area 98
Description of the Northern Test Area 107
Data Collection Procedures 113
Selection of Data Sources 113
Classification of Measures 116
Substitution of Measures 118
Design of Sampling Procedures 121
Description of Sampling Equipment 131
Sampling Accuracy and Rates 136
Data Analysis Procedures 138
Measures, Values, and Utilities 138
Development of Utility Networks 140
Generation of Single Factor Alternatives 141
Generation of Multiple Factor Alternatives 142
Evaluation of Generated Alternatives 142

CHAPTER V - ANALYSIS OF SOUTHERN TEST AREA 144

Investigation of Route Independent Highway Location Factors 144
Derivation of Value Surfaces for the Earthwork Cost Factor 145
Derivation of a Value Surface for the Pavement Construction Cost Factor 155

Page

Derivation of a Value Surface for the Right of Way Acquisition Cost Factor 164
Derivation of Value Surfaces for the Service Benefits Factor 170
Generation of Single Factor Alternatives 179
Results of Analysis for the North-South Corridor . . . 179
Results of Analysis for the East-West Corridor 185
Generation of Multiple Factor Alternatives 189
Results of Analysis for the North-South Corridor . . . 189
Results of Analysis for the East-West Corridor 194
Evaluation of Alternatives 199

CHAPTER VI - ANALYSIS OF NORTHERN TEST AREA 201

Investigation of Route Independent Highway Location Factors 201
Derivation of a Value Surface for the Earthwork Cost Factor 202
Derivation of a Value Surface for the Pavement Construction Cost Factor 207
Derivation of a Value Surface for the Right of Way Acquisition Cost Factor 214
Derivation of Value Surfaces for the Service Benefits Factor 219
Generation of Single Factor Alternatives 230
Results of Analysis for US 52 Route 230
Results of Analysis for State Road 43 Route 236
Generation of Multiple Factor Alternatives 242
Results of Analysis for US 52 Route 242
Results of Analysis for State Road 43 Route 253
Evaluation of Alternatives 258

CHAPTER VII - CONCLUSIONS AND RECOMMENDATIONS 261

Conclusions 261
Recommendations 265

BIBLIOGRAPHY 268

VITA 280

LIST OF TABLES

Table		Page
1	The Highway Planning Hierarchy	5
2	Results of Program VECTOR Analyses	54
3	The Method of Investigation	93
4	The Highway Location Factors Studied	115
5	Data Digitization Speeds on the LARR-V Co-ordinatograph	137
6	Southern Test Area - Results of Statistical Analyses - I	148
7	Southern Test Area - Pavement Construction Cost Values	161
8	Southern Test Area - Results of Statistical Analyses - II	163
9	Southern Test Area - Adopted Rating Scale for Right of Way Acquisition Cost Values	166
10	Southern Test Area - Roadway Ratings	176
11	Southern Test Area - Multiple Factor Analyses	190
12	Northern Test Area - Results of Statistical Analyses - I	205
13	Northern Test Area - Pavement Construction Cost Values	209
14	Northern Test Area - Adopted Rating Scale for Right of Way Acquisition Cost Values	216
15	Roadway Ratings for Northern Test Area	223
16	Northern Test Area - Results of Statistical Analyses - II	225
17	Correlation Coefficients Determined by Comparison of Five Value Surfaces	229
18	Northern Test Area Multiple Factor Analyses	243

LIST OF FIGURES

Figure Page

1. A Hypothetical Route Location Problem Showing the Spatial Relationships of Various Actions Generated and Evaluated 7

2. Alternative Graphical Representations of the Highway Planning Hierarchy 8

3. Alternative Design Procedures 14

4. The GCARS System 16

5. Utility Diagrams of all 26 Design Requirements Studied at a Western Massachusetts Test Site 25

6. Dendogram of Design Requirements Shown in Figure 5. 26

7. Terrain Smoothing to Simulate Cut and Fill Costs . . . 30

8. The Economic Relief Model 31

9. The Digital Terrain Model Coordinate System 34

10. The Digital Terrain Model System 35

11. Flowchart of the DTM Location System Showing Interactions 37

12. An Ultimate Computer-Assisted Highway Design Procedure 38

13. Classification of Numerical Surface Analysis Procedures 46

14. Program Vector Analysis Procedures 52

15. Effect of Triangle Type on "K" 53

16. Relationships between "K" and Strike and Dip Variability 55

Figure | Page

17. Types of Information Resulting From Trend Surface Analysis 65

18. Two Dimensional Regression 66

19. Graph Definitions 81

20. Comparison of Minimum Path Algorithms Based on Computation Times 86

21. Data Analysis Sequence 94

22. Location of Test Areas 97

23. The Seventy-Two Map Quadrangles (Scale 1:24,000) Covering the Southern Test Area 99

24. Map of Southern Test Area Showing Towns and Highways 100

25. Physiographic Diagram of South-Central Indiana 101

26. Engineering Soils Map of Southern Test Area 105

27. Land Use Map of Southern Test Area 106

28. Physiographic Diagram of the Northern Test Area 108

29. Engineering Soils Map of Northern Test Area 110

30. Location of Granular Soils in the Northern Test Area . 111

31. Land Use Map of Northern Test Area 112

32. Origin-Destination Zones in the Northern Test Area . . 114

33. The Three Types of Measures 117

34. Homogeneous and Heterogeneous Discontinuous Measures . 119

35. Sampling Procedures for Discontinuous Measures 123

36. Sampling Procedures for Topographic Maps 125

37. Relationship Between Minimum Sampling Rates and Weighted Variability Number for Fourth and Fifth Degree Trend Surfaces 129

Figure | Page

38. Relationship Between Minimum Sampling Rates and Weighted Variability Number for Original Values Maps 130

39. The LARR-V Digital Coordinatograph 133

40. Southern Test Area Computer-Generated Contour Maps of Trend Surfaces of Degree One Through Five for Topographic Elevations From 1:250,000 Scale Maps 133

41. Southern Test Area Computer-Generated Contour Maps of Trend Surfaces of Degree One Through Five for Topographic Elevations from 1:24,000 Scale Maps 148

42. Production of a Trend Mosaic for Topographic Data - Step 1 - Four Original Fifth Degree Trend Surfaces . . 152

43. Production of a Trend Mosaic for Topographic Data - Step 2 - Eastern and Western Trend Surface Halves Formed by Merging the Surfaces in Figure 42. 153

44. Production of a Trend Mosaic for Topographic Data - Step 3 - The Final Trend Mosaic Formed by Merging the Surfaces in Figure 43. 154

45. Southern Test Area - Map of Residuals to Fifth Degree Trend Surface Fitted to Elevations From 1:250,000 Scale Topographic Maps 156

46. Southern Test Area - Maps of Residuals to Fifth Degree Trend Surface Fitted to Elevations From 1:24,000 Scale Topographic Maps 157

47. Southern Test Area - Map of Residuals to Fifth Degree Mosaic Trend Surface 158

48. Southern Test Area - Computer-Generated Contour Maps of Trend Surfaces of Degree One Through Five for Pavement Construction Cost Values 162

49. Southern Test Area - Contour Map of Pavement Construction Cost Value Surface 165

50. Southern Test Area - Computer-Generated Contour Maps of Trend Surfaces of Degree One Through Five for Right of Way Acquisition Cost Values 168

51. Southern Test Area - Contour Map of Right of Way Acquisition Cost Value Surface 169

Figure Page

52. Southern Test Area Computer-Generated Contour Maps of Trend Surfaces of Degree One Through Five for Town Populations 171

53. Southern Test Area - Population Density Data 173

54. Southern Test Area - Computer-Generated Contour Maps of Trend Surfaces of Degree One Through Five for Population Density Values 174

55. Southern Test Area - Computer-Generated Contour Maps of Trend Surfaces of Degree One Through Five for Quality of Present Highway Network 177

56. Southern Test Area - Contour Maps of Town Populations and Road Network Value Surfaces 180

57. Southern Test Area - Generated Alternatives for Single Factor Analyses 181

58. Southern Test Area - Generated Alternatives for Single Factor Analyses 182

59. Southern Test Area - Generated Alternatives for Single Factor Analyses 183

60. Southern Test Area - Generated Alternatives for Single Factor Analyses 186

61. Southern Test Area - Generated Alternatives for Single Factor Analyses 187

62. Southern Test Area - Generated Alternatives for Multiple Factor Analyses 192

63. Southern Test Area - Generated Alternatives for Multiple Factor Analyses 193

64. Southern Test Area - Generated Alternatives for Multiple Factor Analyses 195

65. Southern Test Area - Generated Alternatives for Multiple Factor Analyses 196

66. Southern Test Area - Generated Alternatives for Multiple Factor Analyses 198

67. The Six Topographic Maps Covering the Northern Test Area 203

Figure | Page

68. Northern Test Area - Computer-Generated Contour Maps of Trend Surfaces of Degree One Through Five for Topographic Elevations 204

69. Northern Test Area - Map of Residuals to Fifth Degree Trend Surface Fitted to Elevation Data 208

70. Northern Test Area - Computer-Generated Maps of Trend Surfaces of Degree One Through Five for Pavement Construction Cost Values 211

71. Northern Test Area - Contour Map of Pavement Construction Cost Value Surface 213

72. Northern Test Area - Computer-Generated Contour Maps of Trend Surfaces of Degree One Through Five for Right of Way Acquisition Cost Values 218

73. Northern Test Area - Contour Map of Right of Way Acquisition Cost Value Surface 220

74. Northern Test Area - Computer-Generated Contour Maps of Trend Surfaces of Degree One Through Five for Trip End Values 226

75. Northern Test Area - Contour Maps of Total Population and Population Density Value Surfaces 227

76. Northern Test Area - Contour Maps of Trip Ends Road Network Value Surfaces 228

77. Northern Test Area - Generated Alternatives for Single Factor Analyses 231

78. Northern Test Area - Generated Alternatives for Single Factor Analyses 232

79. Northern Test Area - Generated Alternatives for Single Factor Analyses 233

80. Northern Test Area - Generated Alternatives for Single Factor Analyses 234

81. Northern Test Area - Generated Alternatives for Single Factor Analyses 237

82. Northern Test Area - Generated Alternatives for Single Factor Analyses 238

Figure	Page

83. Northern Test Area - Generated Alternatives for Single Factor Analyses 239

84. Northern Test Area - Generated Alternatives for Single Factor Analyses 240

85. Northern Test Area - Generated Alternatives for Multiple Factor Analyses 244

86. Northern Test Area - Generated Alternatives for Multiple Factor Analyses 246

87. Northern Test Area - Generated Alternatives for Multiple Factor Analyses 247

88. Northern Test Area - Generated Alternatives for Multiple Factor Analyses 249

89. Northern Test Area - Generated Alternatives for Multiple Factor Analyses 250

90. Northern Test Area - Generated Alternatives for Multiple Factor Analyses 251

91. Northern Test Area - Final Generated Multiple Factor Alternatives and Map of Corresponding Utility Surface 252

92. Northern Test Area - Generated Alternatives for Multiple Factor Analyses 254

93. Northern Test Area - Generated Alternatives for Multiple Factor Analyses 256

94. Northern Test Area - Generated Alternatives for Multiple Factor Analyses 257

95. Northern Test Area - Final Generated Multiple Factor Alternatives 259

ABSTRACT

Turner, Alan Keith Finlay. Ph.D., Purdue University, January 1969. Computer-Assisted Procedures to Generate and Evaluate Regional Highway Alternatives. Major Professors: Robert D. Miles and W. N. Melhorn.

Present highway location analysis procedures concentrate on the geometric and economic aspects of only a few alternatives. This study is concerned with the definition and development of improved procedures to assist the design engineer in rapidly generating and objectively assessing a larger number of alternatives. New procedures are especially needed during the early steps of the planning hierarchy when regional studies are undertaken and generalized alternatives defined.

The principal aims of the study were therefore to investigate and evaluate numerical surface analysis procedures and to apply them, in conjunction with minimum path analysis procedures, to the analysis of alternative regional highway locations. These aims were achieved by designing and testing a prototype Generalized Computer-Aided Route Selection (GCARS) System.

The GCARS System processes suitable measures of each highway location factor selected by the design engineer to produce value surfaces which are later converted to utility surfaces. Utility surfaces may be combined in various proportions to produce multiple factor utility surfaces. Utility networks are constructed on these surfaces. Repeated minimum path analysis of these networks generates a series of alternative locations between any origin and destination, in terms of the selected factors alone or in combination. Evaluation of these alternatives with respect to the first choice alternative determines the sensitivity of the alternatives to the various factors and combinations.

The GCARS System was applied to two test areas within the State of Indiana. Five different factors representing potential costs or benefits were studied in an area covering 3740 square miles in south-central Indiana. Alternative data sources were collected and utilized as measures for several factors, so that a total of nine measures were studied. A second smaller area, including the Greater Lafayette, Indiana area, was selected for more detailed studies. Four factors represented by eight different measures were evaluated in this area.

The main conclusions reached by this research are:-

(1) Computer-aided regional highway location procedures, as utilized by the prototype GCARS System, can assist design engineers in analyzing a larger number of alternatives.

(2) Numerical surface analysis procedures have important applications in the GCARS System during data collection and analysis operations.

(3) There are four important factors which affect regional highway locations. They are (a) earthwork cost, (b) pavement construction cost, (c) right of way acquisition cost and (d) service benefits.

(4) Regional analysis can be performed using generally available data as measures of these factors. However more detailed analyses require specially collected data for several of these factors.

(5) Generation of single and multiple factor alternatives can be accomplished by repeated application of minimum path analysis procedures to utility networks.

CHAPTER I

INTRODUCTION

The Route Location Process

The Role of Transportation

The primary purpose of any transportation system is to serve certain broadly defined goals of society. These may include economic goals, such as growth of commerce; social or socio-economic goals, such as improved accessibility and communication; or political goals, such as increased defensive capability. Thus transportation systems are ultimately evaluated in terms of political and economic, as well as engineering, realities. This evaluation is undertaken at two scales. There is a regional analysis to determine the best transportation systems and there is a detailed analysis to plan the development of any particular link of the overall transportation system.

The transportation engineer has a responsibility at both these planning scales. First, he serves as a technical adviser on a team composed of politicians, economists, regional planners, and engineers who are responsible for determining regional or national transportation systems. The engineer advises this group on all pertinent considerations regarding choice of transportation mode, such as between highways or railroads, and technology, such as between highway types or narrow and standard gauge railroads. Second, the engineer has primary responsibility for locating the most efficient and economical route for any link, or links, assigned to him and forming part of a previously approved transportation system.

A fundamental tenet of democracy is that if enough people have all the facts they will be able to determine, better than any other known method, what is best for the group. It is the engineer's responsibility to analyze physical alternatives and to give the people the facts. The procedures described in this thesis are designed to aid the engineer in performing his twin responsibilities as technical adviser on transportation systems and as principal designer of specific facilities. Because highways are an important form of transport, they are emphasized; although similar techniques could be applied equally well to any form of transportation network.

It is beyond the scope of this thesis to discuss the political aspects of route location, or of its relationship to the national or regional economic goals. This has been done elsewhere [28, 39, 57, 81, 105]*

Applications to Developing Regions

The concept that transportation must serve the broader goals of society applies equally to the so-called "under-developed" areas and to the "developed" areas. Economists, engineers, and regional planners are giving increasing attention to the transportation problems of the developing regions [39, 105].

The transportation problems of developing regions do differ from those of more advanced areas. Any decision to invest in a transportation facility carries with it a number of consequences. The relative importance attached to two broad types of consequences - those affecting users of the facility and those affecting nonusers - differs between developed and developing regions. In highly developed economies the user costs are traditionally given the highest priority. Furthermore, due to the affluence of these societies, quasi-economic factors are given consideration. Reduced travel-time and increased safety are justifiable and generally accepted goals and may override, in part at least, more purely economic considerations such as cost.

---

*Numbers in brackets refer to items in the Bibliography.

In developing areas, the nonuser consequences are generally of higher relative importance. Developing regions are often characterized by minimal transportation networks. Thus the addition of a single link to such a system is much more likely to result in changes to the entire economy, than would the addition of a similar link to an already dense network. Furthermore, developing regions often have scant economic resources so that costs of competing schemes must be critically examined and priorities determined. In discussing this matter Soberman [105] states:-

> "Clearly a strong case can be made for basing transportation policy in developing countries on firmer grounds than are customarily used in the more developed economies. The opportunity cost of ill-advised investments in transportation, in terms of housing, education, and medical investments foregone, is a luxury which most developing countries can hardly afford."

It is believed that the procedures presented in this thesis are applicable to the analysis of transportation links in developing countries. With a combination of economic growth models and these procedures, the engineer could first determine alternative routes, then simulate probable developments resulting from the construction of each, and thus recommend the optimal route in terms of present cost and future economic gain.

The Hierarchical Structure of the Highway Location Process

Careful examination of the highway location process reveals it to be a "hierarchically-structured sequential decision process" [63, 64]. Once it is decided to design a link between specific termini a Region is selected large enough to include both termini and all conceivably feasible routes between them. By a sequence of decisions the engineer defines the routes with greater and greater precision. These steps are for convenience defined as Bands, Corridors, Routes, and Alignments.

These basic steps in the route location process have been named "actions" by Manheim [63, 64]. According to Manheim, each action contains at least two basically different kinds of activities, which he called "search" and "selection". The search activity concerns the generation of alternatives, while the selection activity involves choosing among the alternatives previously generated.

While each of the actions (Region, Bands, Corridors, Routes, and Alignments) is similar because each contains the activities of search and selection, they differ from each other because they are at different "levels" in the location process. Manheim defines levels as follows:-

> "When we compare two kinds of actions and find one that is characteristically specified with less precision than the other, then we say that the more completely specified action is of a lower level than the other."

These actions, when ordered according to their levels, form the "highway planning hierarchy". This relationship is summarized in Table 1. Obviously the higher levels of the hierarchy can only be found in the analysis of longer routes. This is in keeping with the concept that a greater range of choices is possible during the design of longer routes.

TABLE 1

THE HIGHWAY PLANNING HIERARCHY

	ACTION	ACTIVITIES
highest ↑	Region	Search for and select a large area containing all conceivable feasible solutions.
	Band	Search for and select one or more "bands" five to ten miles wide.
LEVELS	Corridor	Search for and select one or more "corridors", two to five miles wide.
↓	Routes	Search for and select one or more "routes" one half to one mile wide.
lowest	Alignment	Search for and select one or more trial alignments, prepare final plans for facility.

Figure 1 represents a map of a hypothetical route location problem and shows the spatial relationship of the various actions involved in the solution. These are lettered in the order they were generated and evaluated. The engineer through a search and selection procedure first determined Region "A". Within this Region, two Bands, "B" and "C" were generated. Within these Bands, Corridors "D", "E", and "F" were generated. Corridor "E" was ranked the best and Route "G" was generated within it. Route "G" would contain one or more Alignments (not shown), each containing minor geometrical differences.

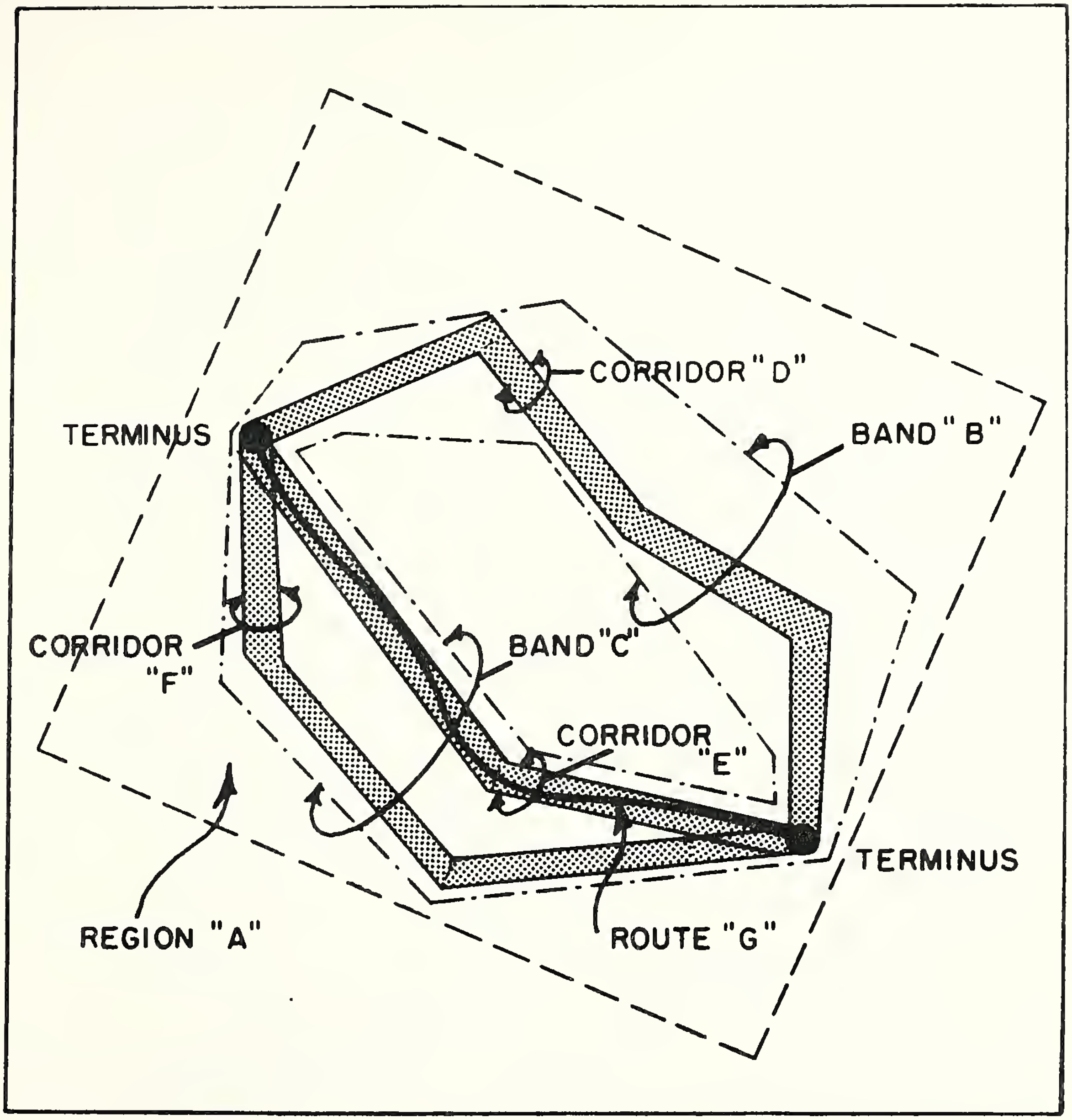
Figure 1 and the description of the solution procedure to this hypothetical problem both suggest a further important condition inherent in hierarchical structure; namely the concept of inclusion. The inclusion relationship between actions can be described in terms of set theory [63]. This is shown graphically in Figure 2-A. Region "A" may be represented as the universal set containing all possible alignments. Within it are located two subsets representing the Bands "B" and "C", within these there are further subsets representing the Corridors, and so on.

A second method of representing the inclusion concept utilizes a dendogram as shown in Figure 2-B. A dendogram concisely summarizes important aspects of the history of a particular route location process. It is a most useful graphical aid in the study of hierarchical structure. From such a diagram can be determined:-

a) The number of actions which have been generated and evaluated.

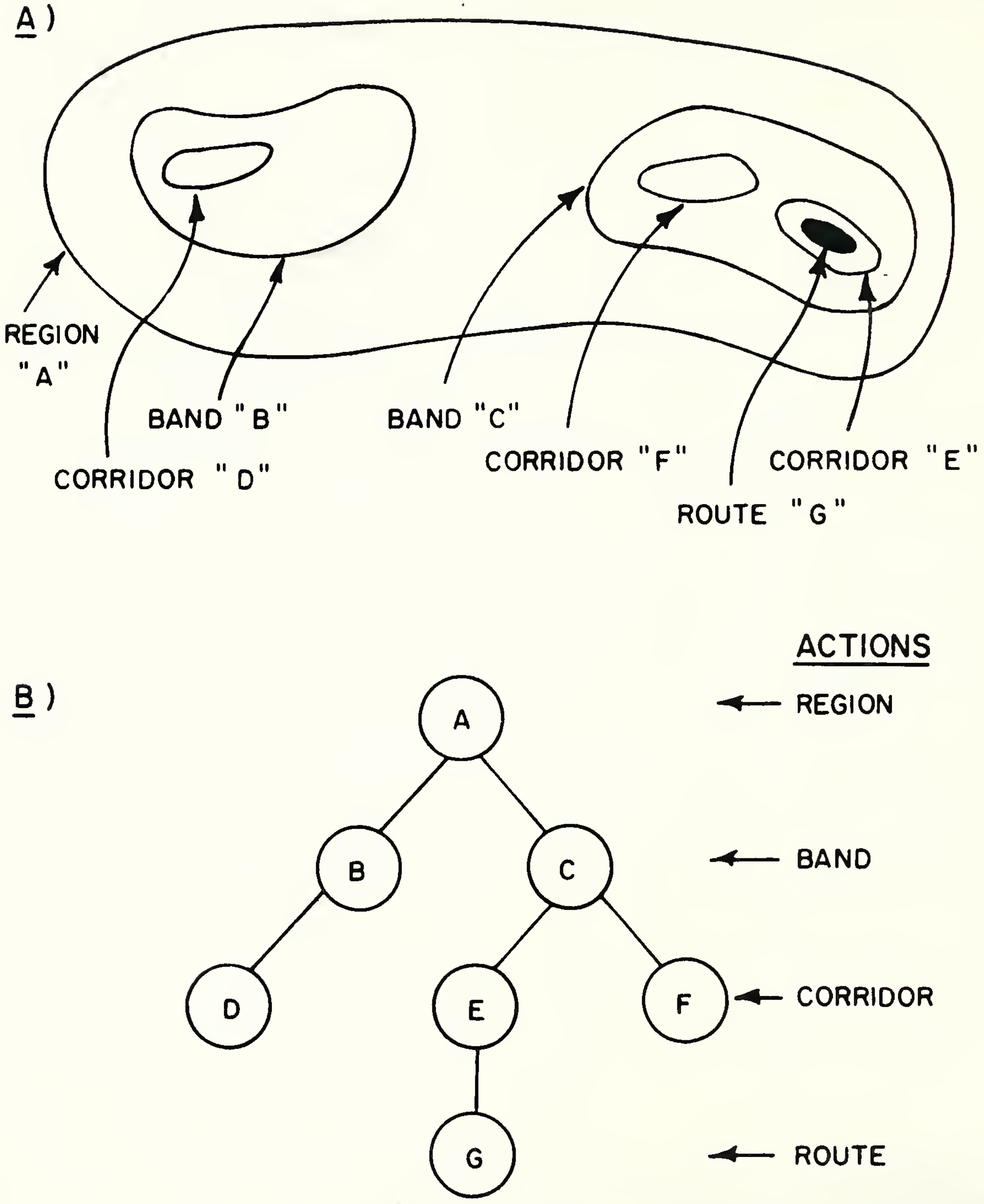
b) The relative levels of these actions and thus the probable sequence of their generation and evaluation.

c) The genealogy of each action - in which actions it is included



(adapted from Manheim)

FIGURE I. A HYPOTHETICAL ROUTE LOCATION PROBLEM SHOWING THE SPATIAL RELATIONSHIPS OF VARIOUS ACTIONS GENERATED AND EVALUATED.



(adapted from Manheim)

FIGURE 2. ALTERNATIVE GRAPHICAL REPRESENTATIONS OF THE HIGHWAY PLANNING HIERARCHY.

and which actions it includes.

Present Highway Location Procedures

In the light of the above discussion, it is most instructive to briefly examine the typical way in which route location is performed by highway departments or consulting engineers in the United States.

The following description was developed by Manheim [63] following conversations with experienced highway location engineers. It is believed to be fairly "typical" of the procedures employed by most states.

Manheim states:-

> "In a typical location process, the following activities can be identified:
>
> a) Reconnaissance:
> Considering a variety of factors, such as general topography, general traffic desires, and political issues, one "band of interest" is generated and picked for further study. A band of interest is an area stretching between the two termini. It may be as wide as several miles, but this will vary significantly with the nature of the terrain.
>
> After reconnaissance, aerial photography is obtained and photogrammetric maps are produced for the selected band of interest.
>
> b) Control points:
> Sets of constraints on the location are generated and examined for their effects. Known as "control points", these constraints may consist of: the termini of the route, obstacles to be underpassed, overpassed, or detoured; locations of interchanges with other routes, etc.
>
> c) Preliminary location:
> For a set of control points, approximate horizontal alignments are generated. These are approximate in that the location of the centerline is not specified precisely, but to about an accuracy of 200' (where the right-of-way of the highway may be 150-300'). For this reason, we can call these approximate alignments "location bands". Approximate profiles of the ground surface along these bands may be taken to aid in evaluating them.

Three or four of the best location bands are selected for further examination.

d) Alignment design:
Within the selected location bands, one or more horizontal alignments are generated and evaluated. The evaluation is on the basis of the ground profile along the centerline.

e) Roadway design:
For alignments which look good, one or more vertical profiles are generated and evaluated.

The best profile is determined for each alignment. The three or four best of these locations are selected for further examination.

f) Interchange studies:
For each location, possible layouts for interchanges with other roads are generated and evaluated.

The single best location, with interchange layouts, is selected.

g) Final design:
The single best location, with interchange layouts, is submitted to final design, in which the geometrics of the facility are specified (generated) precisely, and a detailed economic evaluation made (including details of land takings, construction costs, user costs, etc.)."

The Need for Improvements

Discrepancies are immediately discovered from a comparison of the above description of typical location procedures with the discussion of the hierarchical nature of the highway planning process in its ideal form. The present procedures apparently concentrate on the geometrical aspects of comparatively few alternatives. Economic analysis is almost an afterthought.

In terms of the highway planning hierarchy, present location analysis is confined to the Route and Alignment levels, the lowest two levels of the hierarchy.

However, application of the concept of inclusion immediately identifies the danger inherent in present procedures. If inadequate analysis at the upper levels of the highway planning hierarchy results in feasible alternative Bands or Corridors being overlooked, no amount of detailed analysis at the lower levels will insure the discovery of an optimal design. Suboptimal designs are the best that can be expected.

Under such conditions it is not surprising that special interest groups, frequently looking at a location from a new point of view, have recently successfully challenged final plans for highway development at public hearings [77]. These challenges may result from inadequate review of all factors at higher levels in the hierarchy. The arguments raised by special interest groups are more easily refuted if the costs for alternatives are prepared and the community as a whole is able to weigh the merits of the case.

However, with present techniques, time considerations render it impossible to study more than a few routes. Because these limitations are most apparent at the upper levels of the highway planning hierarchy, procedures to aid in their analysis are the subject of this thesis. Development of new means to rapidly and selectively generate and evaluate alternatives would greatly assist the engineer and lead to economy in design. Suhrbier and Roberts [103] state:-

> "The analysis levels concerned with project location and planning and also overall system design have received somewhat less attention. ...... Since the costs of a project are almost completely determined at these higher levels, it is these levels that should receive future research interest."
>
> "The formulation, design, construction, and implementation of individual models required to fill these "gap" areas of the ultimate man-machine system represents a fertile area for future research."

The Role of the Computer in Highway Engineering

The inadequacies of present planning procedures have been outlined by many researchers in recent years [9, 60, 63, 91, 95, 96]. The rapid development of digital computers naturally resulted in attempts to utilize this new tool in highway location.

The computer was found useful in two areas: in the detailed geometric analysis of alignments for which a number of systems have been developed [9, 60, 70, 71, 92, 93, 94, 95], and in the production of "driver's eye" movies used to simulate a trip along a yet to be built facility [9, 29, 30, 60, 85]. However, use of the computer has lagged in the more generalized analyses required at the upper levels of the highway planning hierarchy. Suhrbrier and Roberts [102] state the current situation quite clearly:-

> "The highway design phases have received the majority of recent research efforts. Systems of digital computer programs now exist which permit detailed analysis of earthwork quantities and which facilitate the computation of right of way, interchange and superelevation geometrics........"
>
> "Although much computer-oriented work has been directed towards the final design aspects of this overall system, investigations are only beginning in such areas as regional network analysis, horizontal alignment selection........"

The reason for this is not hard to find. Computers have no intelligence; they compute according to programmed instructions. Writing a program to perform the decisions involved in even simple route evaluations is a formidable task. Procedures involving linear programming techniques, including Bayesian decision theory, have been suggested [63,64] and appear promising. The absence to date of practical versions of these techniques has resulted in suggestions of using the computer as an aid to design, rather than as the designer. Both man and machine perform those functions for which they are best suited. Generally this means that the machine performs laborious, often repetitive, calculations while the man interprets the results and plans subsequent steps.

Computer-Aided Design Procedures

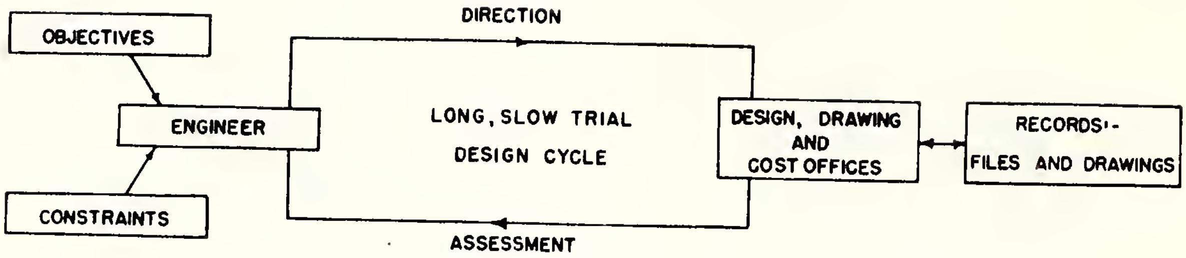
In a recent paper, Lowe, Young, and Lister [60] neatly summarize this concept as follows:-

> "Thus it appeared that the engineer remained a vital and integral part of the system, and that while all the routine mechanical, logical and repetitive operations could be executed much more speedily by the computer, a man would be needed (in the present state of the art) to use his powers of association, assessment, and overall judgment to direct the progression of the design towards its optimum.
>
> So it was that, starting from the concept of a fully computer-designed road, a scheme gradually crystallized for a system which would allow the engineer to obtain from the computer, in the most suitable form for rapid assimilation, objective assessments and quantitative appraisals of the various steps in his design, having given it the simplest possible setting data."

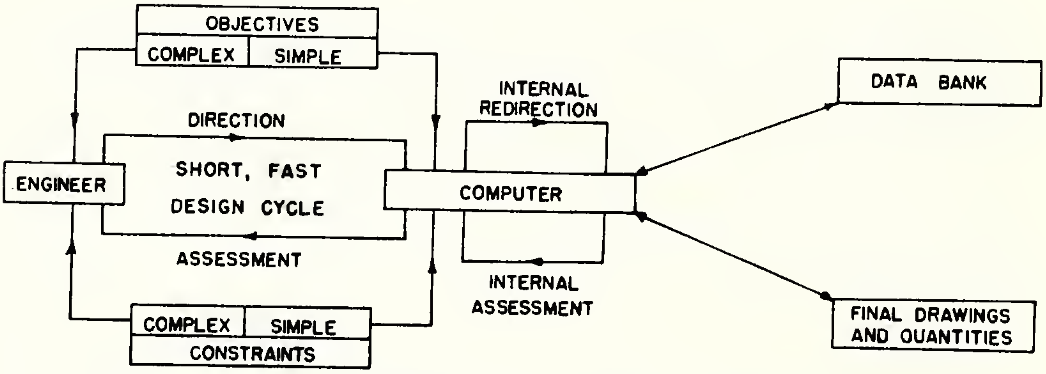
Their concept of a computer-augmented design scheme, as opposed to an entirely manual one, is shown in Figure 3.

In 1957, Roberts [91] outlined the basic characteristics of a system similar to that investigated by this research project. According to him the integration of three "new" (then) tools into a single "smooth system" would greatly aid the design engineer. His three tools were (1) photogrammetric methods, (2) airphoto analysis, and (3) electronic computers. The system would be integrated because,

> "aerial photography would be the basic data collection system, photogrammetry would be the quantitative or metric data system, airphoto analysis would be the qualitative or classified data system, and the electronic computer would be the data reduction and evaluation system."[91]


OBJECTIVES
ENGINEER
CONSTRAINTS
DIRECTION
LONG, SLOW TRIAL DESIGN CYCLE
ASSESSMENT
DESIGN, DRAWING AND COST OFFICES
RECORDS'- FILES AND DRAWINGS

MANUAL DESIGN



COMPUTER AUGMENTED DESIGN

(after Lowe, Young, and Lister)

FIGURE 3. ALTERNATIVE DESIGN PROCEDURES.

Roberts realized that the computer could assimilate and reduce data to a form more readily understandable to the engineer. His suggestion for photogrammetric input data was not followed in this project because adequate topographic maps were available and data could be obtained from them with sufficient accuracy more efficiently with the personnel available. In areas where such maps are lacking photogrammetric techniques would naturally be applied. Airphoto interpretation was used directly and indirectly, for example through the use of soils maps developed from airphoto interpretation, as a source of data on various factors. Roberts suggested the production of "economic relief models" which roughly correspond to the utility surfaces mapped by the computer and used in this research.

The Generalized Computer-Aided Route Selection (GCARS) System

This research program was concerned with the applications of numerical surface analysis procedures to the location of highway routes. Before these procedures could be evaluated however, some system which could utilize them had to be defined. The system developed to utilize these procedures is named the Generalized Computer-Aided Route Selection System (GCARS System). Figure 4 outlines the basic characteristics of this system.

At any level in the highway planning hierarchy, three activities have been identified, the data preparation activity, the search activity, and the selection activity. Manheim defined his search and selection activities [63,64] to include data preparation in the search activity. The three-way subdivision proposed here, and corresponding reduction in the scope of the search activity, is more convenient for discussion of

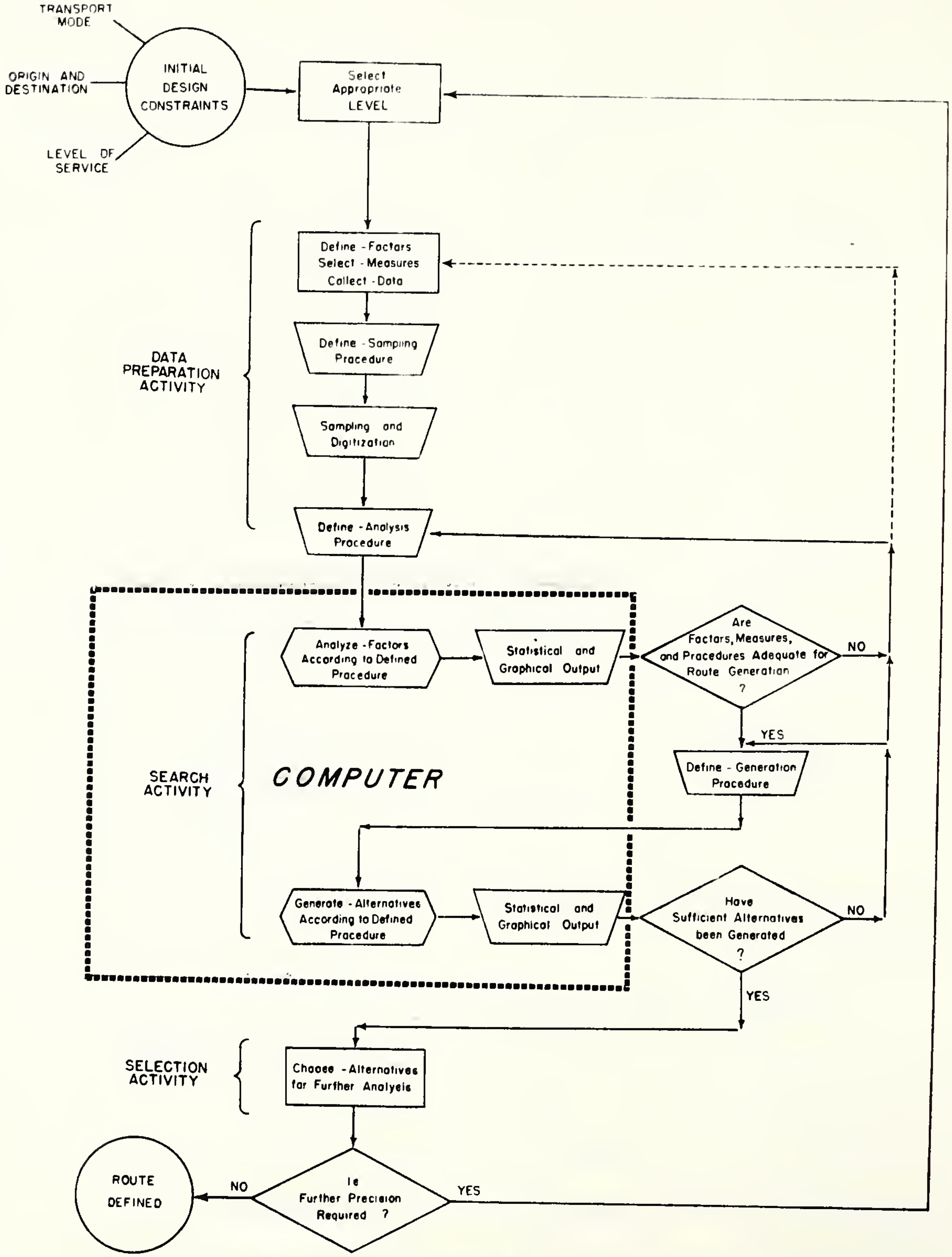

TRANSPORT MODE
ORIGIN AND DESTINATION
LEVEL OF SERVICE
INITIAL DESIGN CONSTRAINTS
Select Appropriate LEVEL
DATA PREPARATION ACTIVITY
Define - Factors
Select - Measures
Collect - Data
Define - Sampling Procedure
Sampling and Digitization
Define - Analysis Procedure
SEARCH ACTIVITY
COMPUTER
Analyze - Factors According to Defined Procedure
Statistical and Graphical Output
Are Factors, Measures, and Procedures Adequate for Route Generation ?
NO
YES
Define - Generation Procedure
Generate - Alternatives According to Defined Procedure
Statistical and Graphical Output
Have Sufficient Alternatives been Generated ?
NO
YES
SELECTION ACTIVITY
Choose - Alternatives for Further Analysis
Is Further Precision Required ?
NO
YES
ROUTE DEFINED

FIGURE 4. THE GCARS SYSTEM.

the GCARS System.

It should be noted that the computer is dominant in only one of the three activities, the search activity. The selection activity is entirely left in the hands of the design engineer, since it is assumed that he is best qualified to make the right decision given all necessary facts. Man is also dominant in the data preparation activity, although he is aided by the computer, or other machinery, in the computations required to design the sampling methods and in the actual data digitization. Thus the GCARS System is truly a computer-aided design system, and, in common with all such procedures, is greatly dependent on "man-machine interchanges" of information [69]. Such interchanges must be rapid and convenient to both parties if the system is to be effective. The research is concerned with the problems of "man-to-machine" and "machine-to-man" information exchanges.

Use of the GCARS System begins when the design engineer is given the basic problem definition. Generally he will be told the origin and destination of the route, the mode of transportation he is to design for (road, railroad, etc.), and the level of service to be supplied (four-lane interstate route, primary state route, etc.). If certain intermediate points must be served, the analysis can be considered as a number of design problems, each concerning the location of a link between a single origin and destination. The primary function of the design engineer is to determine the route having the lowest "social cost" and "highest social benefit" [77]. The GCARS System is designed to assist him in finding this route.

Once the problem has been outlined, the design engineer must first select an appropriate level in the highway planning hierarchy at which to begin his analysis. He must next define those factors having some bearing on the evaluation of alternatives. For each factor so chosen he must then select a measure to be used in studying that factor and finally he must collect data for these measures. For example, a chosen factor may be soil type; and the measure selected a county engineering soils map The data collection would consist of obtaining a copy of the map.

Conversion of the collected data to a form acceptable to the computer requires man-to-machine interchanges of information. Basically the data must be "digitized", converted to numerical form. This should be accomplished as simply as possible, yet be reproducible. Digitization generally requires sampling of the collected data, thus the design of suitable sampling techniques is an important part in the design of a successful GCARS System. As shown in Figure 4, the final aspects of the Data Preparation Activity involve the definition of a sampling procedure, sampling and digitization of the data, and selection of suitable data analysis procedures to be performed in the search activity.

The machine dominated search activity can be subdivided into a data analysis phase and a generation phase. The analysis phase involves the use of a variety of Numerical Surface Analysis Procedures. Only when the design engineer is satisfied that each of the various factors is described adequately does he initiate the generation phase which is based on minimum path analysis techniques.

Communication from the machine-to-man is important during the search activity when data manipulation and analysis is being performed by the computer. The design engineer must be able to rapidly comprehend the results. This requires graphical and statistical output so that the machine-to-man communications are brief enough to allow the man to extract the important information quickly and easily. The development of adequate computer-generated graphical output procedures is therefore another important part in the design of a successful GCARS System.

Once the alternatives have been generated by the machine, the design engineer performs his most important function; he must choose those alternatives which he believes to be the most promising. This is the selection activity. Once the most promising alternatives have been chosen the engineer must then decide if further refinement is possible at a lower level of the highway planning hierarchy. If further refinement is possible through use of the GCARS System, the entire procedure is repeated at a lower level in the highway planning hierarchy, as shown by the arrow returning to the top of Figure 4. If the analysis has been performed at the _Route_ level of the hierarchy, no further refinement is possible through use of the GCARS System. Further refinement is obtained at the _Alignment_ level through use of geometric design systems such as the Massachusetts Institute of Technology Digital Terrain Model described in Chapter II.

Purpose of Study

This study was undertaken with a five-fold purpose:-

1) to investigate previously developed numerical surface analysis techniques which have been successfully applied to a variety of earth science problems.

2) to evaluate the applicability of these techniques to the analysis of highway route location factors, in particular their application in conjunction with minimum path analysis procedures.

3) to develop and evaluate man-machine interchange systems to facilitate the exchange of information between design engineers and digital computers.

4) to develop a suitable computer-aided highway location system for the upper levels of the highway planning hierarchy.

5) to identify future research needs in the field of highway route selection.

Scope of Study

The study was concerned with the design of a computer-aided highway location system for the Band, Corridor, and Route levels of the highway planning hierarchy. Computer-aided design systems, such as the Massachusetts Institute of Technology Digital Terrain Model (DTM), were available to assist in the generation and evaluation of alternatives at the lowest levels of the hierarchy, so no further study was made at this level.

System design and evaluation was based on the following six system design concepts:-

1) The system shall include methods of rapid and efficient information storage, processing and retrieval, through the use of digital computers.

2) The system shall provide effective and convenient methods of man-machine information interchanges to increase the engineer's decision-making capabilities.
3) The system shall be designed to incorporate suitable quantitative measures of all pertinent factors.
4) The system shall include techniques of ordering alternatives by analysis of available data.
5) The system shall be flexible, to allow the analysis of pertinent factors alone or in combination.
6) The system shall have general compatability with available lower-level design systems, such as the Digital Terrain Model, in terms of resolution and data collection.

Two test areas were selected in the State of Indiana as described later. In these areas the computer-aided design system concepts were tested in natural environments, rather than for purely hypothetical cases. As a result of these experiments some measure of the utility of computer programmed data storage, processing and retrieval functions was obtained and the basic requirements of suitable man-to-machine and machine-to-man information exchange procedures were determined.

CHAPTER II

REVIEW OF PROPOSALS FOR IMPROVEMENTS IN HIGHWAY LOCATION AND DESIGN TECHNIQUES

In recent years engineers and planners have increasingly accepted the necessity for a broader approach to the study of the social and economic consequences of various highway development proposals. As a consequence there have been a number of attempts to develop suitable methods for determining and choosing a single "best" plan in terms of a number of conflicting criteria. Although considerable work in this area has been done in North America, independent research also has been undertaken in Europe.

At least three different approaches have been utilized. These are:- 1.) Graphical route selection procedures, 2.) Computer-assisted design procedures, and 3.) Computer-generated drivers-eye movies of proposed facilities.

None of the procedures so far proposed is applicable to the entire highway planning hierarchy. However, many of them have considerable application to the analysis of certain types of highway location and design problems.

Graphical Route Selection Procedures

Many engineers and planners have utilized graphical methods to determine optimal route locations. No doubt a large number of such studies have been performed without extensive documentation. The few examples from the literature described here are believed to be typical of these procedures.

Graphical procedures, in their simplest terms, contain the following steps:-

(1) identification of the pertinent factors,

(2) development of maps at a consistent scale, showing each factor,

(3) preparation of overlays for each factor showing on a gray scale various levels of utility for highway locations in terms of that factor,

(4) the combination of these overlays in some fashion to determine the "best route" for all factors, as shown by coincidence of gray scales.

McHarg [77] described a recent study in New Jersey that utilized a simple graphical procedure. He assumed that the "best route" was "that which provides the maximum social benefit at the least social cost." It was further assumed that the least social cost alignment would avoid areas of high social value and areas of "physiographic obstructions" which would raise construction costs. "Physiographic obstructions" included items such as steep slopes, bridges, poor foundations, and easily erodable soils.

Twelve parameters were studied; each was plotted on a transparent overlay which contained three levels. Zone 1 was the highest cost of obstruction and was shaded darkest, Zone 2 was an intermediate cost and shaded a medium tone, Zone 3 was the area of lowest cost and was left unshaded. When the twelve overlays were superimposed, a single trumpet shaped zone of "least social cost" was discerned. This corridor was then examined and found to be the alignment of "maximum social utility" in terms of future economic development and aesthetics.

As a result of this analysis a previously announced, but unpopular, interstate development plan was amended.

A much more detailed study of the utility of graphical procedures in route location was performed at MIT by Alexander and Manheim [2]. A test site was chosen in western Massachusetts along Interstate - 91. A series of 26 design requirements was developed. The objective was to determine an optimal route in terms of all 26 requirements. For each requirement a utility diagram was constructed which indicated the relative desirability of each point, for a highway passing through it, in terms of that requirement. These diagrams contained a range of grey tones from white to black. The darker the tone at a particular point, the better that location for a highway location in terms of that requirement. (Note that this is opposite to McHarg's convention.) Figure 5 shows the utility diagrams for all 26 requirements.

From theoretical considerations, Alexander and Manheim were able to show that it is possible to determine a best sequence for combining the 26 diagrams. Complex problems can be solved if their conflicts are solved one at a time. This subdivision into subsets results in the formation of a hierarchically structured tree. The tree developed for their problem is shown in Figure 6.

This tree was determined as follows. Each pair of requirements was studied to see if they were in conflict. This was decided by studying

1 EARTHV

2 COMFORT

3. REGIONAL

4 LOCAL LAN

5 OBSO

NOTE: Th

FIGURE 5. U
MASSACHUSET

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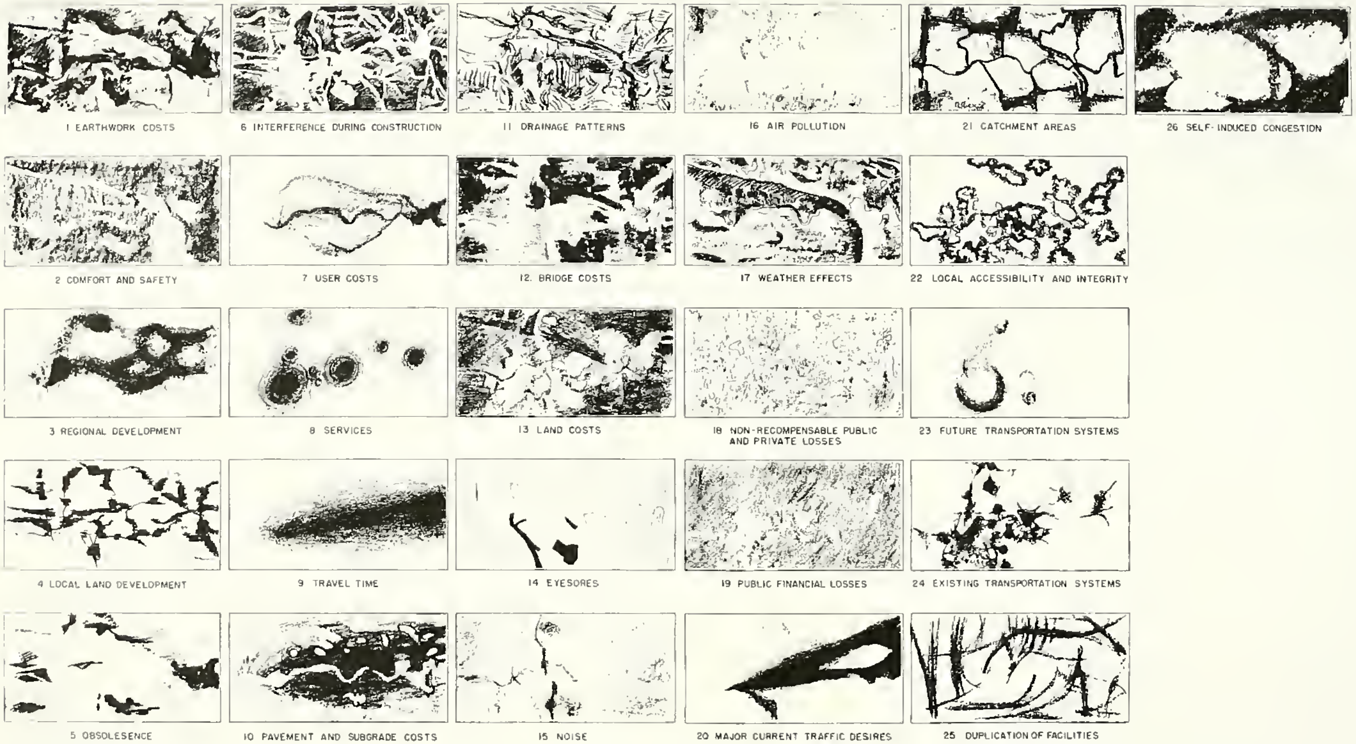


1 EARTHWORK COSTS

2 COMFORT AND SAFETY

3 REGIONAL DEVELOPMENT

4 LOCAL LAND DEVELOPMENT

5 OBSOLESENCE

6 INTERFERENCE DURING CONSTRUCTION

7 USER COSTS

8 SERVICES

9 TRAVEL TIME

10 PAVEMENT AND SUBGRADE COSTS

11 DRAINAGE PATTERNS

12. BRIDGE COSTS

13 LAND COSTS

14 EYESORES

15 NOISE

16 AIR POLLUTION

17 WEATHER EFFECTS

18 NON-RECOMPENSABLE PUBLIC AND PRIVATE LOSSES

19 PUBLIC FINANCIAL LOSSES

20 MAJOR CURRENT TRAFFIC DESIRES

21 CATCHMENT AREAS

22 LOCAL ACCESSIBILITY AND INTEGRITY

23 FUTURE TRANSPORTATION SYSTEMS

24 EXISTING TRANSPORTATION SYSTEMS

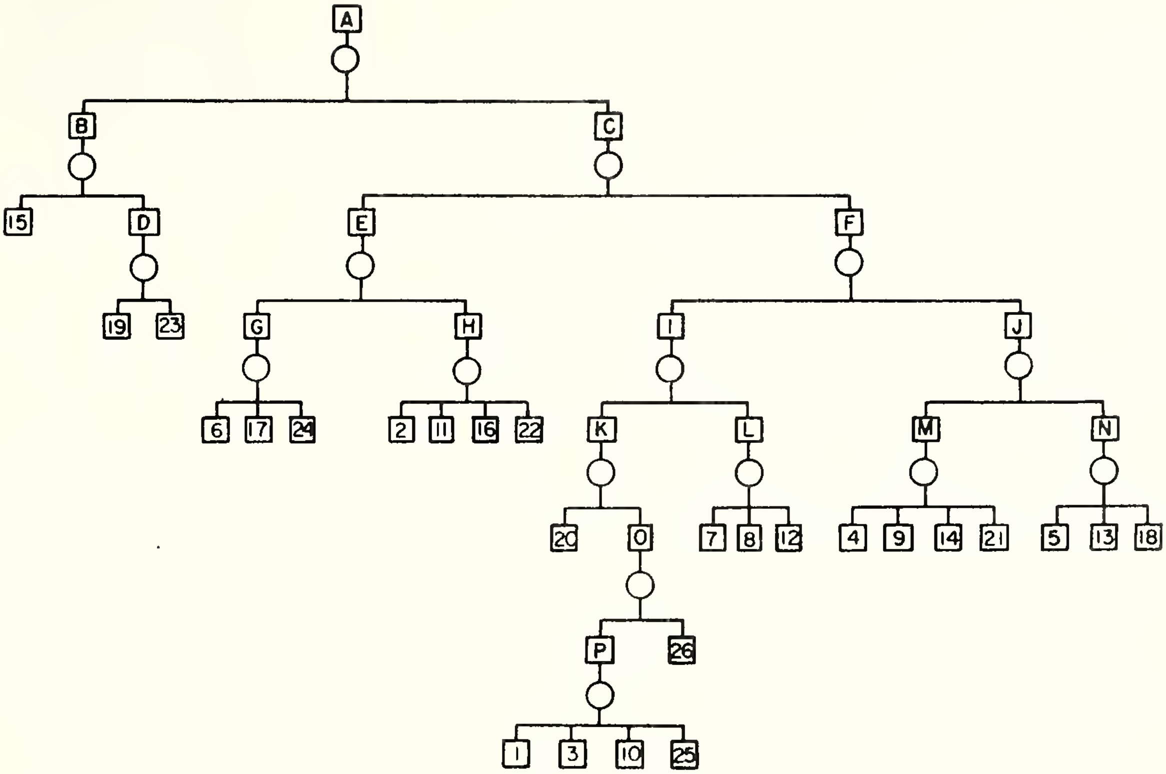
25 DUPLICATION OF FACILITIES

26 SELF-INDUCED CONGESTION

NOTE: The darker the tone the better the area.

(after Alexander and Manheim)

FIGURE 5. UTILITY DIAGRAMS OF ALL 26 DESIGN REQUIREMENTS STUDIED AT A WESTERN MASSACHUSETTS TEST SITE.



LEGEND

2 Original Factor Diagrams

○ Photographic Composite Diagrams

A Modified Composite Diagrams

(after Alexander and Manheim)

FIGURE 6. DENDOGRAM OF DESIGN REQUIREMENTS SHOWN IN FIGURE 5

the two utility diagrams; if one diagram was the opposite of the other, conflict existed. A graph was constructed with 26 vertices, one for each requirement, links were drawn between each pair of vertices for which a conflict existed. This set of all possible requirements was subdivided into two subsets which were connected by as few links as possible. This was repeated until the original set was completely subdivided into its constituent elements. This "hierarchial decomposition" of the set of requirements was performed on the computer [1].

Starting at the lowest levels of the tree, Alexander and Manheim photographically superimposed each prescribed group of diagrams. The relative weight of each constituent diagram was adjusted to bring out the strongest possible organized pattern in the composite. A transparency of the composite was projected onto a drawing board and the image redrawn so as to "bring out its essential organizational features." Emphasis was placed on those parts of the pattern showing features such as continuity and consistent direction.

Each modified composite diagram was now treated as an original diagram. In this way the analysis proceeded up the tree; the cycle of photographic superposition, projection, and modification being repeated until the top of the tree was reached. The final modified diagram gave the solution to the location problem.

Alexander and Manheim also investigated alternative highway interchange designs utilizing similar graphical procedures [3].

In spite of Alexander's and Manheim's pleas to the contrary, the writer believes that most graphical procedures are particularly liable to operator bias. Subjectivity is bound to enter the analysis either during the construction of the individual overlays for each factor or in the extraction of the essential patterns in the composities. Elimination of such bias appears difficult.

Computer-Assisted Design Procedures

Roberts' 1957 Proposal

Probably the earliest important paper on this subject was written by Paul O. Roberts in 1957 [91]. The paper presented the basic outline of a system similar to that developed in this research project. Roberts' ideas were apparently never acted upon, perhaps because computer applications were still in their infancy and highway planners were uncertain as to the value of his proposals.

Roberts suggested that in the future highway location analysis would require an integrated system including (1) the engineer to supply judgment, (2) photogrammetric and airphoto interpretation methods for data collection, and (3) the computer for data storage and manipulation. Thus he suggested a computer-aided design system. The paper includes two concepts fundamental to the present research, namely (1) the use of terrain smoothing to approximate all possible grade lines and thus simulate cut and fill problems, and (2) additivity of several factors to obtain an "economic relief model" which would be analyzed to determine the best route.

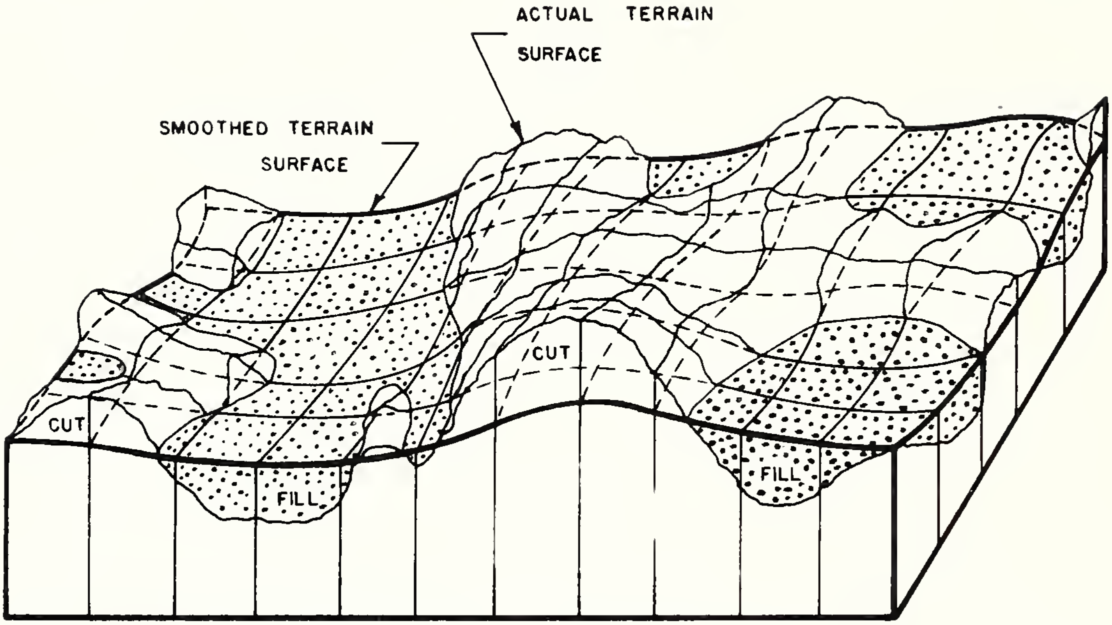
However, Roberts was often vague as to the actual computational procedures that were to be used on the computer, or else he suggested techniques that appear difficult or impractical to apply.

Figure 7 is a reproduction of Roberts' concept of terrain smoothing to determine cut and fill problems. It is an excellent representation of the relationship between a fitted regression surface and a natural terrain. Roberts did not suggest regression procedures but rather suggested that a type of moving average be employed. Regression procedures are more objective and thus more desirable than moving average methods.

The "unit cost models" shown in Figure 8 are roughly comparable to the "utility surfaces" of the present research. Roberts suggested that sampling of each factor on a rectangular grid be used to generate each surface. Such a procedure is not as efficient as a procedure utilizing irregularly spaced sample locations. Grid values tend to repetitiously sample large uniform areas and may easily miss small details. If the grid size is reduced so as to include smaller details, the total number of samples rises rapidly, adding to the data storage and processing problems.

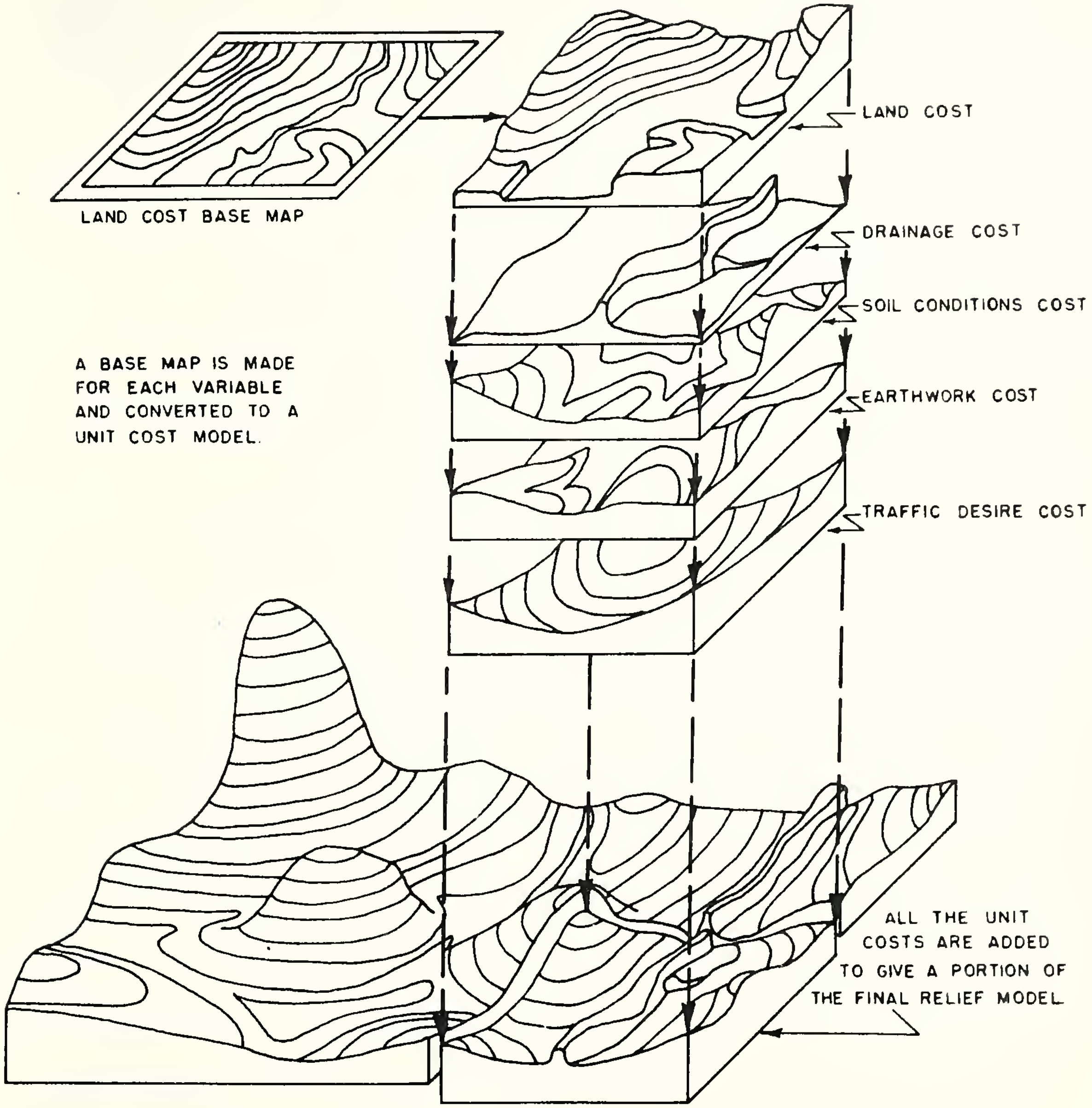
Roberts suggested that all factors should be reduced to a single metric, the dollar. He has been criticized for this [2]. More recently O'Flynn [81] discussed this problem at some length.

> "In the task of measurement of outputs, very difficult problems arise. This is due to the variety of dimensions and distinct scales of value which exist for all the objectives and the related outputs. Usually any group of outputs comprises some which have measurable consequences in economic terms. There are others which cannot be reduced to the same common denominator of market value. In addition there are the outputs of an intangible nature such as the aesthetical aspects."..."There is considerable difficulty in quantifying some of these outputs on a ratio scale, or on any scale, and the problem becomes even greater when an attempt is made to establish their market values. In order to give some dimension to these outputs, use can be made of the casuistic and psychological theories of value. The latter concept attempts to quantify people's value or feelings



(after Roberts)

FIGURE 7. TERRAIN SMOOTHING TO SIMULATE CUT AND FILL COSTS.


LAND COST BASE MAP
A BASE MAP IS MADE FOR EACH VARIABLE AND CONVERTED TO A UNIT COST MODEL.
LAND COST
DRAINAGE COST
SOIL CONDITIONS COST
EARTHWORK COST
TRAFFIC DESIRE COST
ALL THE UNIT COSTS ARE ADDED TO GIVE A PORTION OF THE FINAL RELIEF MODEL

(after Roberts)

FIGURE 8. THE ECONOMIC RELIEF MODEL.

> of value for an output such as noise level. Generally, a weak ordering is possible but attempts to introduce an interval scale have not been successful..." O'Flynn concluded "The most suitable approach is to outline the precise physical magnitudes of the non-market outputs, avoiding the use of questionable value functions."

Roberts had the foresight to suggest that the computer could be used to select the optimal route in terms of cost. However he suggested linear programming methods with alignment specifications as the limiting criteria. Such methods have yet to prove applicable to this problem. The current research used minimum path analysis to select the routes.

The Digital Terrain Model

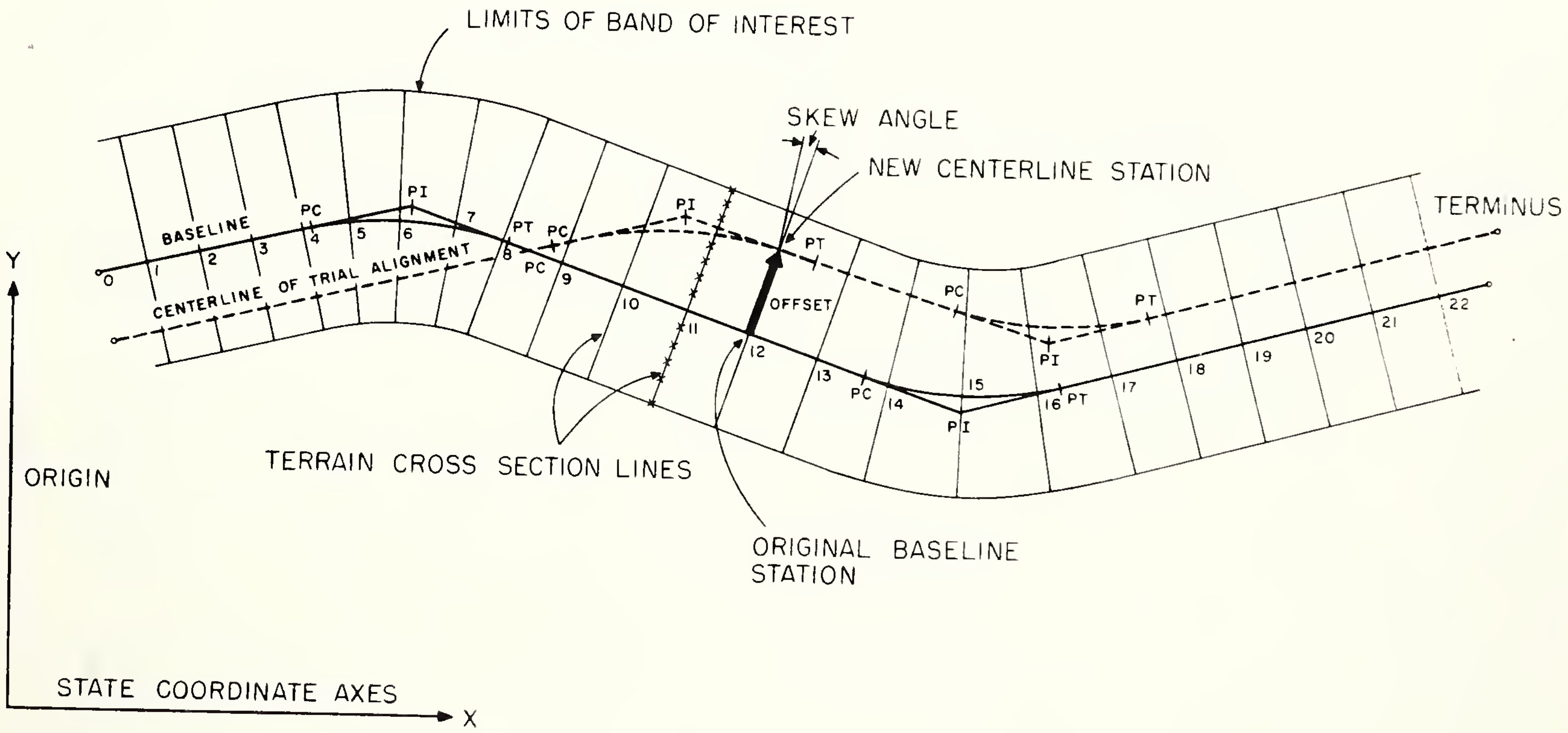
In 1956 the Civil Engineering Department of the Massachusetts Institute of Technology began studying computer applications to highway planning and design. A large number of researchers have been involved, including Roberts, and an extensive literature now exists [70, 71, 92, 93, 94, 95, 96, 103]. By 1960 this team had succeeded in developing an integrated computer-oriented highway design system for the lowest level (Alignment) of the highway planning hierarchy. The system was called the Digital Terrain Model (DTM), because the first developments were directed towards the geometric analysis of alternative horizontal and vertical alignments. Later additions to the system included provisions for economic analysis of other factors such as right of way, structure, and vehicle operating costs; however, the term Digital Terrain Model has been retained as the system identification.

The DTM System requires the engineer to first select a "band of interest", in the terminology of this thesis a Route. Within the Route a baseline is defined. This serves as the X-axis of the data coordinate system and is composed of straight line segments connected by curves, as required by the shape of the Route. The terrain data is measured along lines normal to this baseline called cross-section lines. Sample points are measured from left to right across each cross-section. Distances are measured with respect to the baseline, points on the left having negative signs, those on the right having positive signs. The spacing of the cross-section lines and the sampling densities along them are matters of engineering judgment. Figure 9 summarizes these relationships.

The engineer must also select a series of trial alignments. As shown in Figure 9, each trial alignment centerline is defined with respect to the baseline and consists of interconnecting straight line and curved segments.

The most recent versions of the DTM System include four stages [95, 96]. These are shown diagrammatically in Figure 10. The DTM Location System and DTM Design System are similar in structure and in input-output characteristics. However, there are significant differences due to the different purposes of the Location and Design Systems. Since the DTM Location System is intended for use early in the location studies the constituent programs are somewhat simpler and more generalized than the equivalent programs in the DTM Design System used later in the planning process when more exact analysis is required.

These differences can be shown by comparing (1) the fill volumes obtained by the two systems and (2) their running times. Such measures are greatly dependent on characteristics of the test area. However, in gently rolling terrain in central Massachusetts with cross-sections every 200 feet, cut and fill volumes determined by the two systems differed by about three percent. At the same time the DTM Location System ran about



(after Roberts and Suhrbier)

FIGURE 9. THE DIGITAL TERRAIN MODEL COORDINATE SYSTEM.

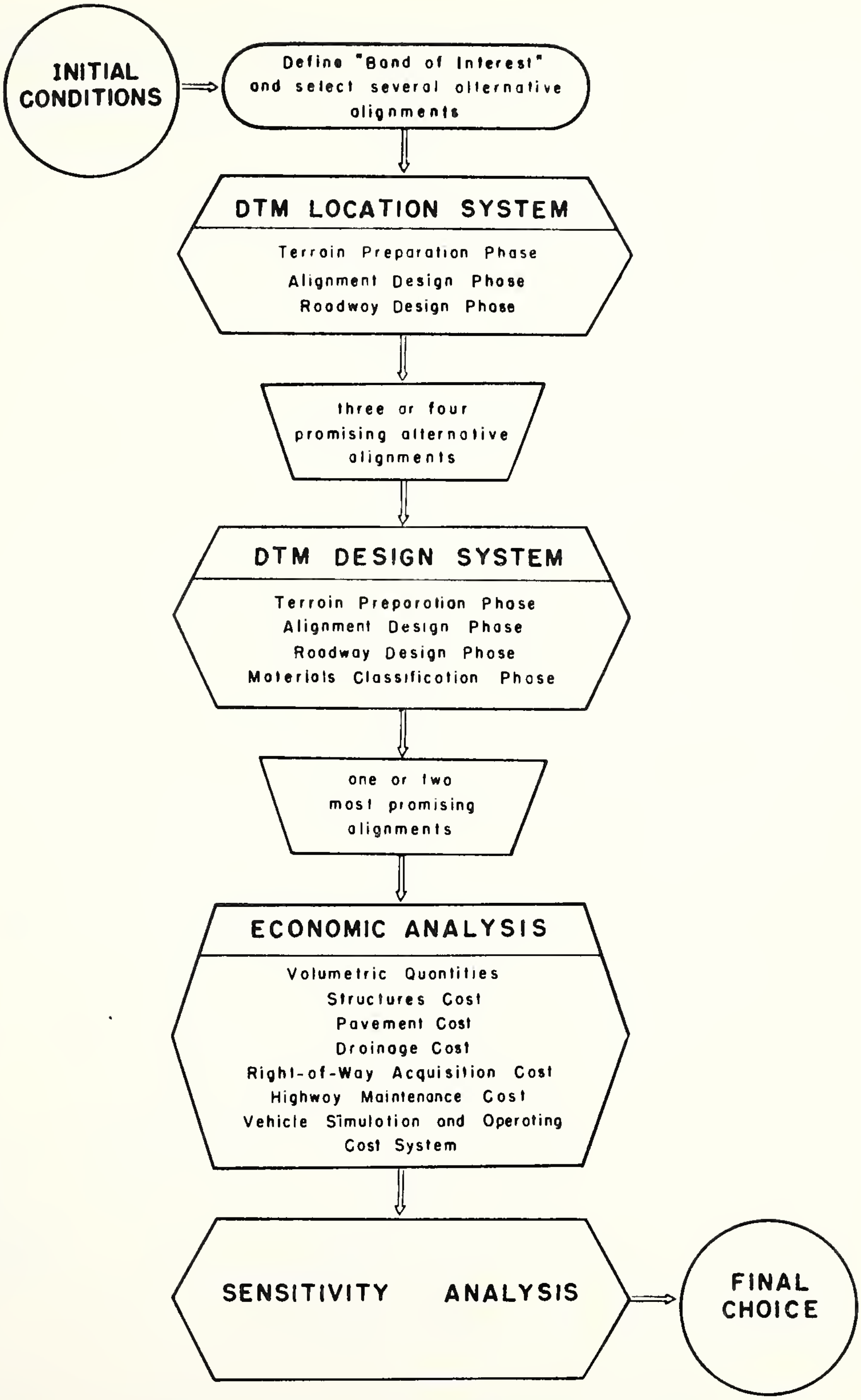

INITIAL CONDITIONS
Define "Band of Interest" and select several alternative alignments
DTM LOCATION SYSTEM
Terrain Preparation Phase
Alignment Design Phase
Roadway Design Phase
three or four promising alternative alignments
DTM DESIGN SYSTEM
Terrain Preparation Phase
Alignment Design Phase
Roadway Design Phase
Materials Classification Phase
one or two most promising alignments
ECONOMIC ANALYSIS
Volumetric Quantities
Structures Cost
Pavement Cost
Drainage Cost
Right-of-Way Acquisition Cost
Highway Maintenance Cost
Vehicle Simulation and Operating Cost System
SENSITIVITY ANALYSIS
FINAL CHOICE

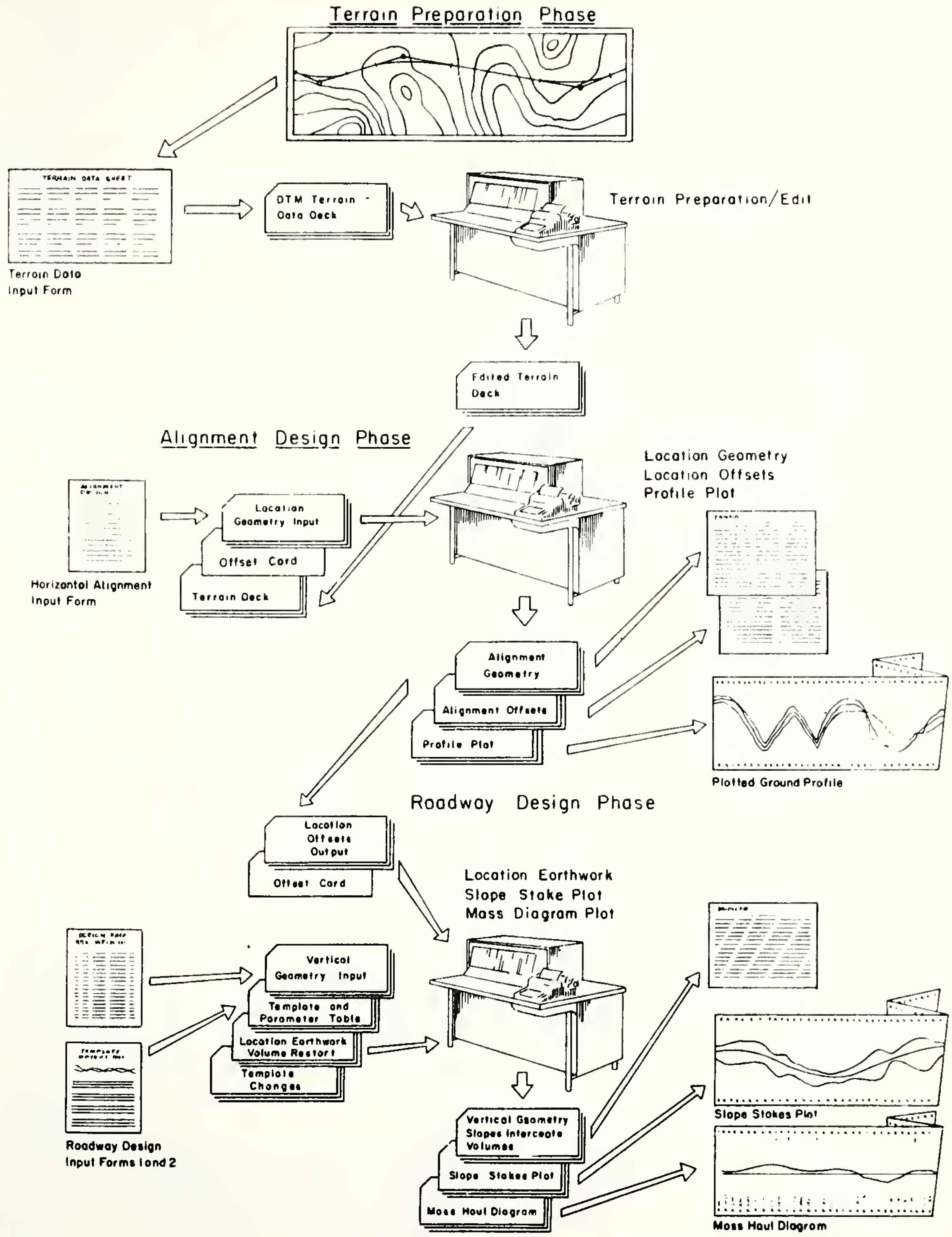
FIGURE 10. THE DIGITAL TERRAIN MODEL SYSTEM.

five times faster than the DTM Design System; equivalent programs in the Roadway Design Phase on an IBM 1620 computer analyzed nineteen miles and four miles of road respectively, in one hour of computation time [96].

The system is an excellent example of the computer-aided design concept. The interactions of the various programs and phases in the DTM Location System are shown in Figure 11. The DTM Design System is similar while the Economic Analysis Stage requires several man-to-machine and machine-to-man information exchanges. The existence of so many man-machine interchanges naturally led to the development of graphical machine generated output as an integral part of the system. Early versions of the DTM System produced some character plots by listing specially prepared cards on an IBM 407 accounting machine. Such plots are of limited use due to their low resolution and the delays involved in their production. More recent versions of the DTM System incorporate capabilities for the production of continuous-line plots from an on-line CALCOMP plotter. The plots are produced more or less concurrently with the design process and are valuable additions to the analysis of many factors. The ultimate version of the DTM System is shown in Figure 12.

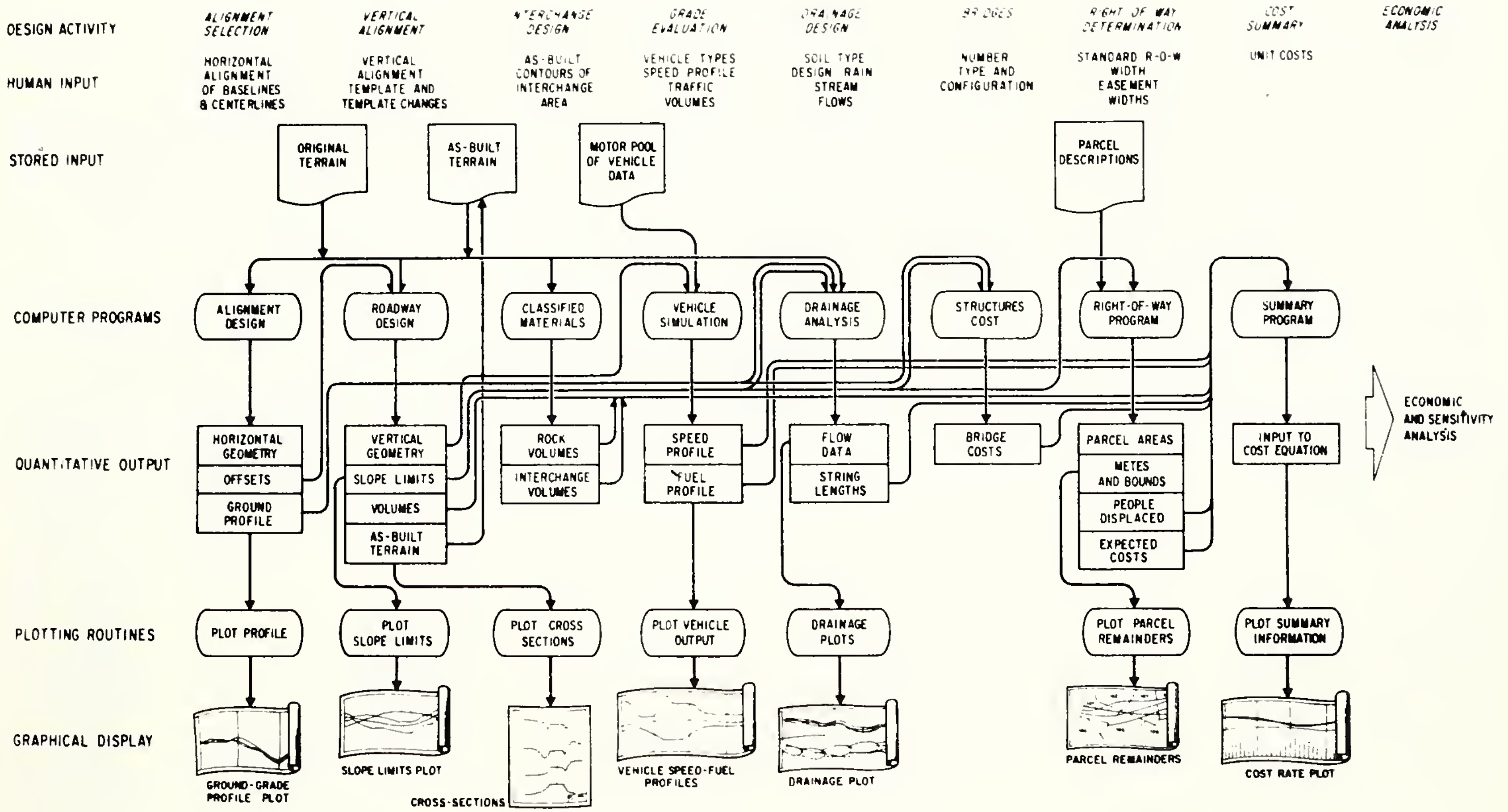
The ROADS System

The MIT Department of Civil Engineering has in recent years been developing an Integrated Civil Engineering System known as ICES. ICES is designed for easy programming of engineering problems on IBM System/360 Computers through the use of a simplified computer language. Various subsystems of ICES are being developed to solve problems in various areas of civil engineering. Of these subsystems COGO, for coordinate geometry computations; BRIDGE for bridge design; and ROADS, for highway location



(after Roberts and Suhrbier)

FIGURE 11. FLOWCHART OF THE DTM LOCATION SYSTEM SHOWING INTERACTIONS.



(after Roberts and Suhrbier)

FIGURE 12. AN ULTIMATE COMPUTER-ASSISTED HIGHWAY DESIGN PROCEDURE.

and design, have particular application to highway route analysis.

While not yet officially released, ROADS is understood to be an expanded version of the DTM System containing some advanced capabilities. When available, it should assist in further developments in highway location analysis.

The CARD System

Lowe, Young and Lister [60] have developed a Computer Augmented Road Design (CARD) system. The system has been applied experimentally to road design in Britain, and performs design functions similar to those performed by the latest versions of the DTM system.

The CARD system can be subdivided into three parts:-

a) terrain data reduction and collation

b) horizontal and vertical alignment design

c) assessment of the designs.

The system was programmed for a medium sized computer of British design (an Elliott 803). As discussed in Chapter I, Lowe, Young, and Lister discovered that a computer-aided design procedure was the most practical approach with present technology. Thus man-machine interchanges of information were developed as part of the overall system.

Terrain elevations obtained from ground or aerial surveys are reduced to grid elevations by interpolation. A grid size of 50 feet is the usual standard. Computer generated contour maps are produced at a scale of 1:2,500 by an on-line digital (incremental) plotter. Such maps are used to verify the terrain data.

After studying the terrain and other factors, the design engineer can select a horizontal alignment by defining curve radii and the coordinates of tangent intersections. The computer refines this data, develops a detailed centerline location, and calculates and plots a longitudinal profile.

Using this longitudinal profile the engineer prepares a vertical alignment. This is refined by the computer to give elevations at fifty foot intervals, of the roadway center and edges, taking into account super-elevation considerations.

Computer-generated perspective views of the roadway, machine calculated earthwork quantities and automatically plotted cross-sections are used in the assessment of the proposed designs.

The system designers suggest that, on the basis of limited testing, the CAPD system reduces design costs about six times and design time about fifteen times.

The IE.GI System

This system was developed in France. The initials IE.GI stand for the system title, in French, which may be translated as Imposed Geometric Electronic Design [9, 30]. Development began in 1962, and an improved second version became available in 1967. Since 1965, the IE.GI system has aided in the design of 700 miles of divided highway each year; some 2000 miles of "freeway style" highways have been designed to date using this program [30]. These figures indicate this system to be by far the most widely used of all the systems so far proposed. Like the other systems, it includes computer-generated graphical output as an aid in man-machine information exchanges.

The program utilizes a "numerical ground image," which is "a set of points on the ground, suitably distributed along the project study strip, and given by their orthogonal coordinates X, Y, and Z in the chosen reference system" [30]. Interpolation of these points to prepare cross-sections or longitudinal profiles is performed by fitting a second-degree polynomial surface to all nearby points according to a weighted-least-squares method. It is reported that this technique can be accomplished at a speed of about 900 points per minute and results in "good accuracy" [9, 30].

The system consists of six sections. The first section produces a detailed horizontal alignment, including all spiral calculations, given a general alignment by the design engineer. A computer generated plot of the alignment is produced on a digital plotter.

The second section allows the designer to specify "structural zones," which are areas along the project for which certain geometric, geologic, or economic parameters can be considered as constants. Such information is needed by sections three and five. This section also locates cross-sections, and bridges, and calculates super-elevation geometrics.

The third section utilizes the previously prepared "numerical ground image." In conjunction with section one it calculates and draws (on a plotter) the longitudinal profile along the project centerline; with section two it develops and plots ground profiles along each cross-section. A subsection converts coordinate data to a form suitable for locating the alignment in the field.

The fourth section refines and develops a smooth vertical profile, given its broad characteristics by the design engineer.

The fifth section provides (1) calculations and computer-generated plots of all cross-sections, (2) earthwork volume calculations, and

(3) slope-stake plots showing the outward limits of cuts-or-fills.

The sixth section can produce two types of computer-generated plots. A map of the alignment, showing centerline, pavement edges, and slope limits can be produced for the entire alignment. Alternatively, a perspective view can be prepared for any requested point in the alignment to give a driver's impression of the finished project. A series of such views can be requested and assembled to produce a cartoon-type movie of the driver's view while driving along the road.

Computer-Generated Driver's Eye Movies

The DTM, CARD, and TE.GI systems all use computer-generated graphics as an aid in information exchange and design evaluation. The value of such graphical aids should not be underestimated. Highways are geometrical entities and the visualization of their designs before construction is an aid in improving design standards and continuity.

The manual production of large numbers of accurate perspective drawings required to produce driver's eye movies is impractical. In 1960 "Perspectographs", machines which optically created perspective projections from horizontal and vertical projections, were developed and used in France to aid in preparing sketches of road alignments [30]. With such a machine, two skilled operators could prepare one perspective projection in a half a day. Such a production rate was much too slow except for special studies.

In recent years a number of comparatively low-cost commercial digital incremental plotters have become available. By suitable programs, these convert numerical values into small step movements, generally 0.01 inch or less, and thus produce accurate line plots in ball-point or india-ink.

Much more expensive cathode ray tube (CRT) display devices are also available. These have the advantage of having display times (of the entire image) of less than one second, as opposed to several minutes for similar images on the incremental plotters.

As graphical output devices became available perspective plotting of roadway elements was attempted. At least four groups are currently working on, or have recently utilized, perspective plotting applications to highway design. These groups are:-

1) a British group connected with the CARD system [60]
2) a French group connected with the TE.GI system [9, 30]
3) the Ontario Department of Highways [29]
4) the Texas Transportation Institute [85].

The first two groups applied perspective plotting of roadway elements as part of their respective system designs. Perspective plots were used as a final route assessment procedure. The French system appears to be more advanced and has been applied to the problems of sign posting and underpass design, as well as to the study of rural highway sight distances. Generally the computer-generated output needs additional shading, elimination of hidden lines, and so on. This is accomplished by human draftsmen at the rate of one perspective per man-hour [30].

The Ontario Department of Highways system is designed for analysis of the corridor as a whole, as well as for alignment design. Corridors are represented either by a series of cross-sections lying perpendicular to the line of sight, or by a series of grid lines. Movies of these corridors are produced with viewing heights of perhaps 100 feet above the ground. Later, specific alignments are checked by driver's-eye movies.

The Texas system is utilized to check specific alignment problem sections. Problems of roadside sign placement, interchange visibility, and loss of sight distance are studied for particular areas.

Costs of such procedures vary with the types of computers and plotters used and with the details shown on the prepared views. Costs for the French system are reported as approximately $2.00 per view [30]. However, through equipment modifications the French hope to reduce their costs to $0.20 per view. The Texas system reports about $1.25 per view [85]. Costs for the other systems are not available.

Although the present research made extensive use of computer-generated contour maps, no attempt was made to develop computer-generated perspective drawings as part of this project. Use of computer-generated movies to study the general characteristics of alternative routes, as suggested by the Ontario Department of Highways, appears to be a logical and useful extension of the computer graphics capabilities.

CHAPTER III

REVIEW OF PROCEDURES TO BE EVALUATED

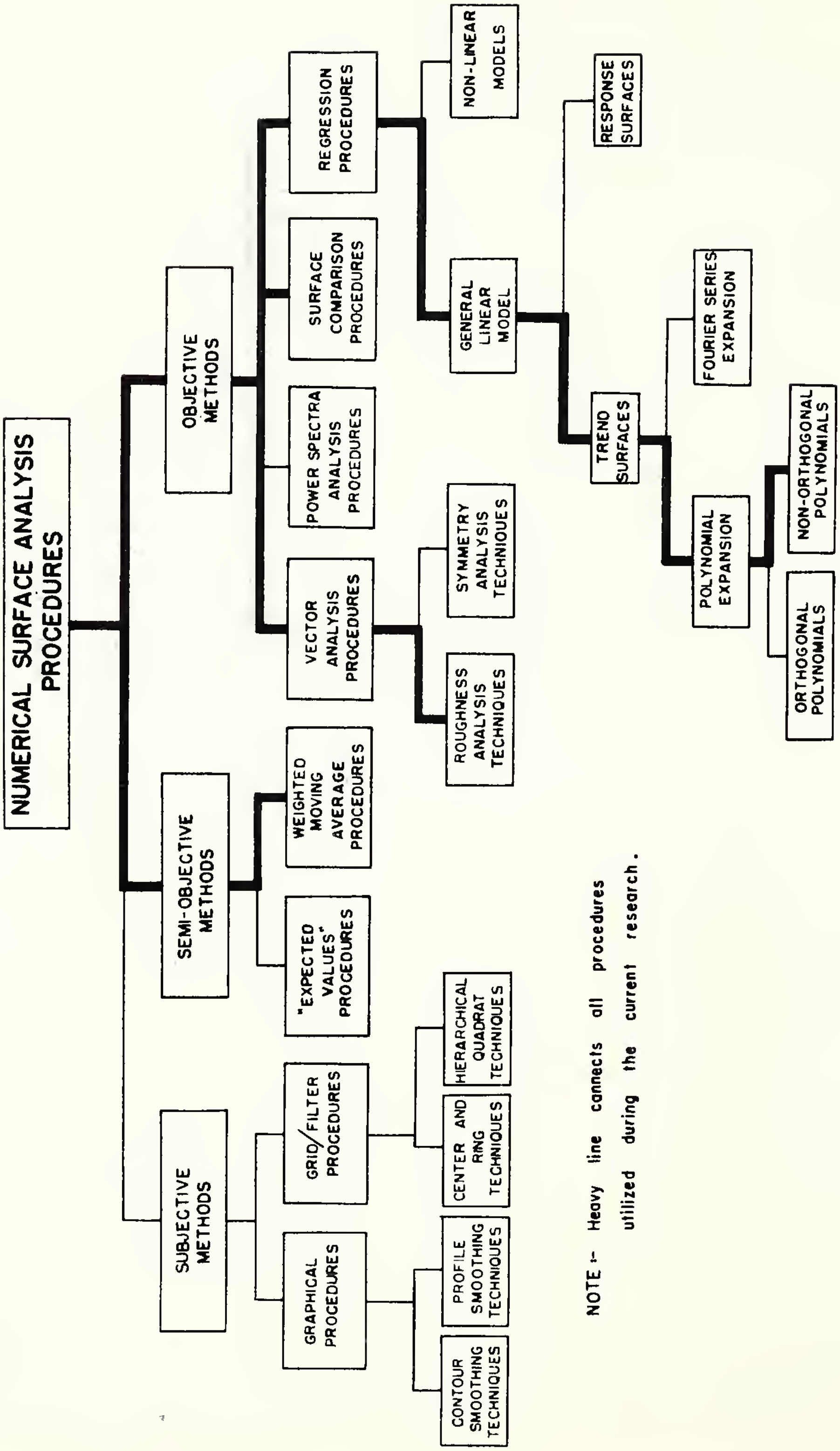
Numerical Surface Analysis Procedures

The analysis and interpretation of spatially or functionally related observations involves a number of inter-related steps which may be collectively called numerical surface analysis procedures. These individual steps require, to varying degrees, some type of graphical display so that the results of the analysis can be readily understood. The most common form of graphical display for three-dimensional data is the contour (or isopleth) map. Maps are a basic form of geographic communication because they supply information with the immediacy of a single picture, rather than serially in the form of many observations.

Review of the various numerical surface analysis procedures indicates that at least three classes of procedures may be recognized. These classes are:-

1) subjective methods,
2) semi-objective methods, and
3) objective methods.

Figure 13, developed from a chart prepared by Chorley and Haggett [17], shows these three classes and lists the important procedures belonging to each. The three classes have an historical basis. The subjective methods predate the debut of digital computers as research tools; the semi-objective methods in part were developed during the 1950's when the


NUMERICAL SURFACE ANALYSIS PROCEDURES
SUBJECTIVE METHODS
SEMI-OBJECTIVE METHODS
OBJECTIVE METHODS
GRAPHICAL PROCEDURES
GRID/FILTER PROCEDURES
"EXPECTED VALUES" PROCEDURES
WEIGHTED MOVING AVERAGE PROCEDURES
VECTOR ANALYSIS PROCEDURES
POWER SPECTRA ANALYSIS PROCEDURES
SURFACE COMPARISON PROCEDURES
REGRESSION PROCEDURES
CONTOUR SMOOTHING TECHNIQUES
PROFILE SMOOTHING TECHNIQUES
CENTER AND RING TECHNIQUES
HIERARCHICAL QUADRAT TECHNIQUES
ROUGHNESS ANALYSIS TECHNIQUES
SYMMETRY ANALYSIS TECHNIQUES
GENERAL LINEAR MODEL
NON-LINEAR MODELS
TREND SURFACES
RESPONSE SURFACES
POLYNOMIAL EXPANSION
FOURIER SERIES EXPANSION
ORTHOGONAL POLYNOMIALS
NON-ORTHOGONAL POLYNOMIALS

NOTE :- Heavy line connects all procedures utilized during the current research.

FIGURE 13. CLASSIFICATION OF NUMERICAL SURFACE ANALYSIS PROCEDURES.

best computers were quite crude by today's standards; the objective methods reflect the use of increasingly sophisticated mathematical and statistical procedures on modern computers. The subjective and semi-objective methods are concerned primarily with map production and contain few, if any, statistical tests. The more recent objective methods normally include statistical tests, and are often entirely based on statistical theory.

A detailed examination of the various statistical concepts used by the objective methods is beyond the scope of this thesis. However, a description of the numerical surface analysis procedures shown in Figure 13 allows for the introduction of appropriate techniques into the current research and also serves to show the general utility of these procedures. Conversion of statistical concepts to applied numerical surface analysis procedures has been accomplished largely by earth scientists and the literature cited reflects this fact.

Subjective Methods

As shown in Figure 13, the subjective methods are grouped into either graphical procedures or grid/filter procedures. Any graphical method involves considerable ambiguity since it depends to some extent on subjective decisions by the operator. A graphical method using a contour smoothing technique of extremely subjective nature was described by Wooldridge and Linton [132]. The most commonly used techniques involve the construction of several parallel or intersecting profiles which are smoothed, generally by eye, then adjusted until a set of internally consistent values is obtained on a rectangular grid. These grid values are used to produce a contour map [51, 80].

The second group of selective methods, the grid/filter type are largely restricted to center point and ring techniques. In their simplest form, a circle of unit radius is centered on each grid point and values obtained by interpolation on the circumference are averaged to give the center grid-point value [33,51]. More complex multiple-ring methods have been devised and are widely applied to geophysical prospecting [80].

Haggett [34] used another but similar technique, the hierarchical quadrat method, in which a series of square cells (quadrats) of increasing area are drawn around each control point and average values obtained. Large quadrats produce maps showing broad regional trends while small quadrats produce maps sensitive to local fluctuations in the data.

Semi-Objective Methods

The two most important semi-objective methods are the expected-values procedure and various weighted moving average procedures.

The expected-values method was developed to provide a more objective criterion for subdividing an observation into local and regional components [51]. The mean values of the rows and columns of rectangular arrays of control points are used to compute the expected value of a point in terms of the characteristics of both the row and the column in which it lies. These expected values are considered to represent the regional component. The differences between the expected values and original control point values are considered to represent the local component.

Weighted moving average procedures include many computational varieties. A method developed by Tobler [113] was extensively used in the current project to interpolate irregularly spaced observations to regularly spaced (gridded) values, a necessary preliminary to the performance of many objective comparison tests and the production of computer-generated contour maps.

A weighted moving average procedure determines the value of each grid point from the values of a set number of nearby original data points. These observations are weighted in importance depending on their relative distance to the grid point being evaluated. The selection of the weighting function and of the number of points to be used in the evaluation is a subjective decision which has to be made by the operator [123]. Objectivity is given to the procedure by its adjustment of the "area of influence" for each interpolation to the local original sampling density. Thus the technique is best considered as semi-objective since the same procedure will give consistent results to any particular set of data, but the choice of the "best" procedure requires subjective decisions on the part of the operator.

Empirical testing of an algorithm developed by Tobler [113] indicated that it "gives reasonable results....which are comparable with those obtained by the fitting of local polynomials, but is computationally much simpler." Further testing during the current research suggests that the algorithm smoothes the data a maximum of 10 percent of the data range for highly erratic data, but that the smoothing rarely exceeds two percent of the data range, for commonly encountered data. The algorithm was programmed in the MAD language by Tobler and translated into Fortran IV by Turner [114] as part of this research project.

Objective Methods

The objective methods in Figure 13 include a great variety of procedures which are grouped into four subsections: (1) vector analysis procedures, (2) power-spectra analysis procedures, (3) surface comparison procedures, (4) regression procedures. Of these, only power spectra analysis procedures were not utilized, at least to some degree, in this research.

Vector Analysis Procedures:- Vector analysis procedures are designed to develop statistical measures of vector orientations and/or dispersions. They are subdivided into those techniques which ignore the directional or symmetry aspects of the vector distributions and those which take symmetry aspects into account. This latter type has been evaluated by Loudon [58, 59] and Whitten [130] in studying the geometry of folded strata. Their procedures involve the use of eigenvectors as a rotation matrix to transform direction cosines of field observations measured with respect to arbitrary axes to the framework of the principal fold axes. The resulting eigenvalues are measures of fold characteristics parallel to each axis. Loudon also developed methods of computing six fold-shape attributes which are independent of fold size [58]. The symmetry procedures are not utilized in the current research.

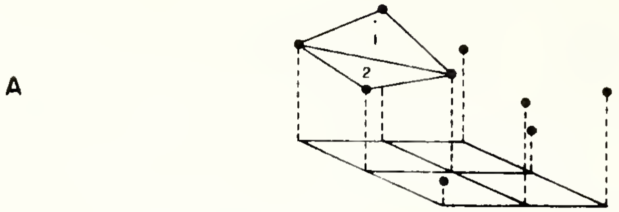
The analysis of surface roughness, defined as "the presence of nonsystematic elevation changes," is an application of vector analysis procedures that ignoresdirection or symmetry considerations. Under such conditions a different type of analysis is possible, and is for convenience labeled "roughness analysis techniques," in Figure 13.

Roughness analysis techniques are based on the theoretical work of Fisher [26] which has been amplified and developed by Watson [121], Steinmetz [107], and Hobson [41]. Hobson developed a FORTRAN IV computer program which was adapted by Turner and Miles [119] and applied to terrain roughness determinations.

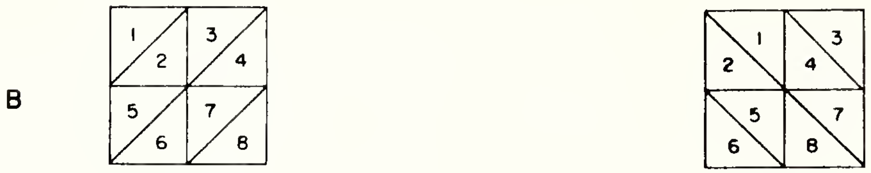
The computations are quite simple. Within a rectangular array of elevation readings, a set of intersecting triangular planar surfaces is defined by groups of three adjacent values as shown in Figure 14-A. Two different sets of triangles (Type 1 and Type 2) are obtained from the same data array by redefining the triangle corners as shown in Figure 14-B. Normals to these planar elements are represented by unit vectors. Fisher's dispersion factor, K, [26, 41, 119] indicates the variability or spread of the unit vectors; it takes on small values for highly dispersed distributions characteristic of "rough" areas (Figure 14-D) and extremely high values for low dispersions characteristic of "smooth" areas (Figure 14-C).

Turner and Miles [119] analyzed twenty-five terrain types, as shown in Table 2. Thirteen were measured on standard topographic quadrangle maps and with one exception were located within Indiana. A further twelve analyses were made on specially surveyed micro-terrain maps prepared by Stone and Dugundji [108]. As a result of these analyses the following conclusions were made:-

1) roughness analysis can be performed at any scale, provided suitable maps or elevation data are available.
2) Fisher's dispersion factor, K, is an excellent descriptor of terrain roughness. Because of the very large range of K

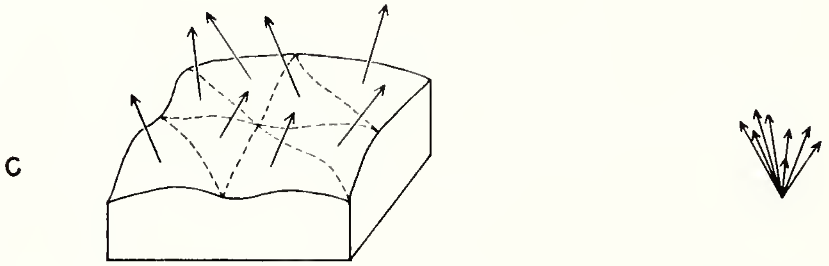


DEFINITION OF TRIANGULAR PLANES FROM ELEVATION MATRIX



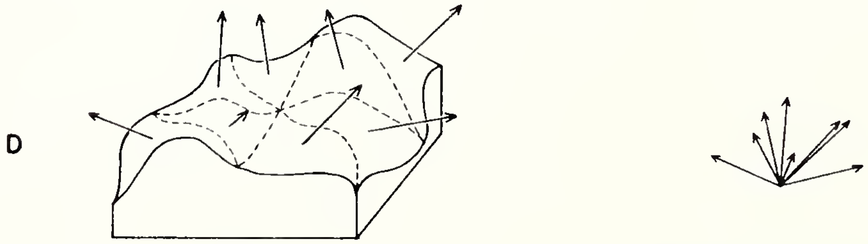
TYPE 1 TRIANGLES

TYPE 2 TRIANGLES



"SMOOTH" TERRAIN

LOW VECTOR DISPERSION

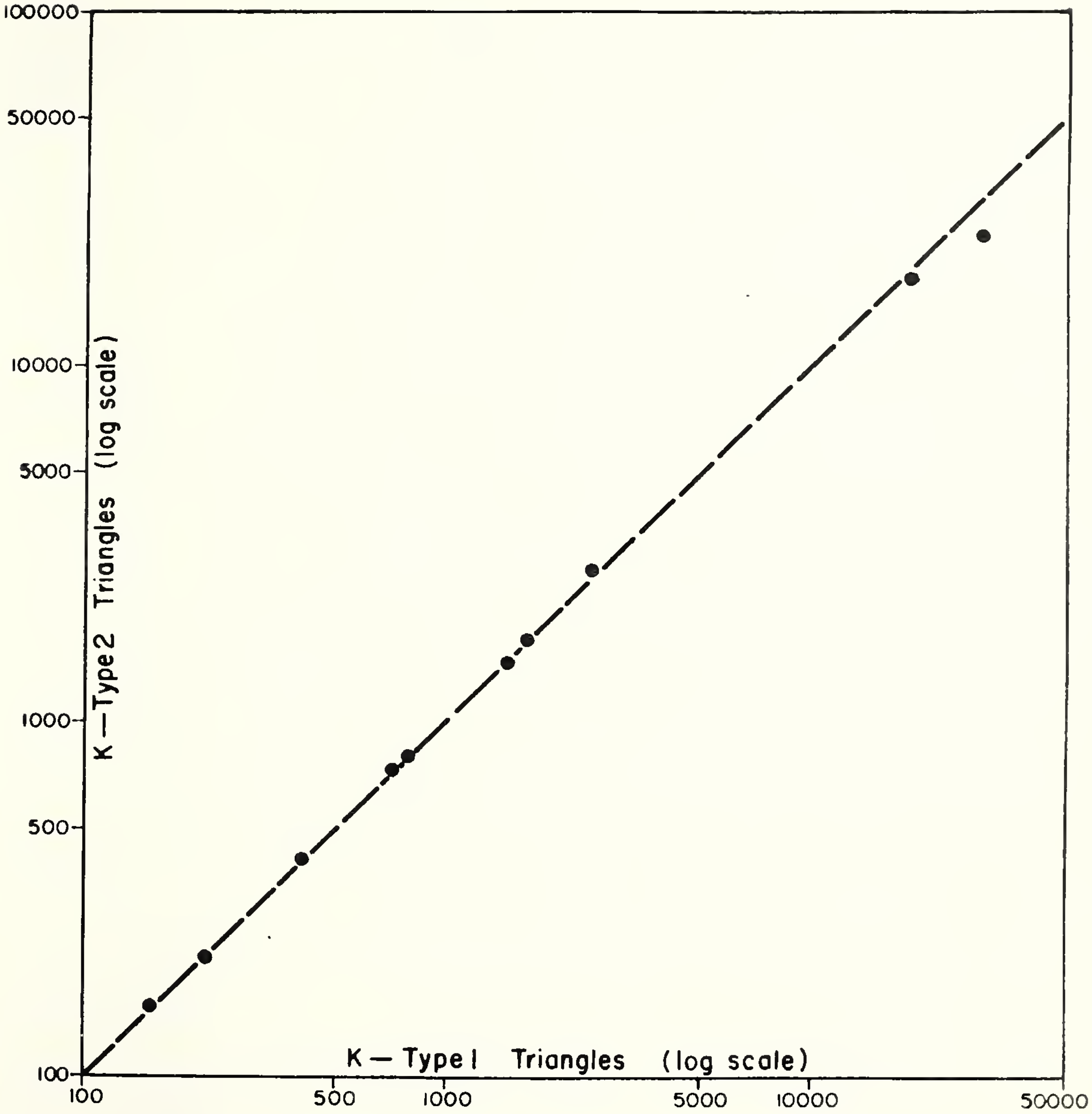


"ROUGH" TERRAIN

HIGH VECTOR DISPERSION

(adapted from Hobson)

FIGURE 14. PROGRAM VECTOR ANALYSIS PROCEDURES.



(after Turner and Miles)

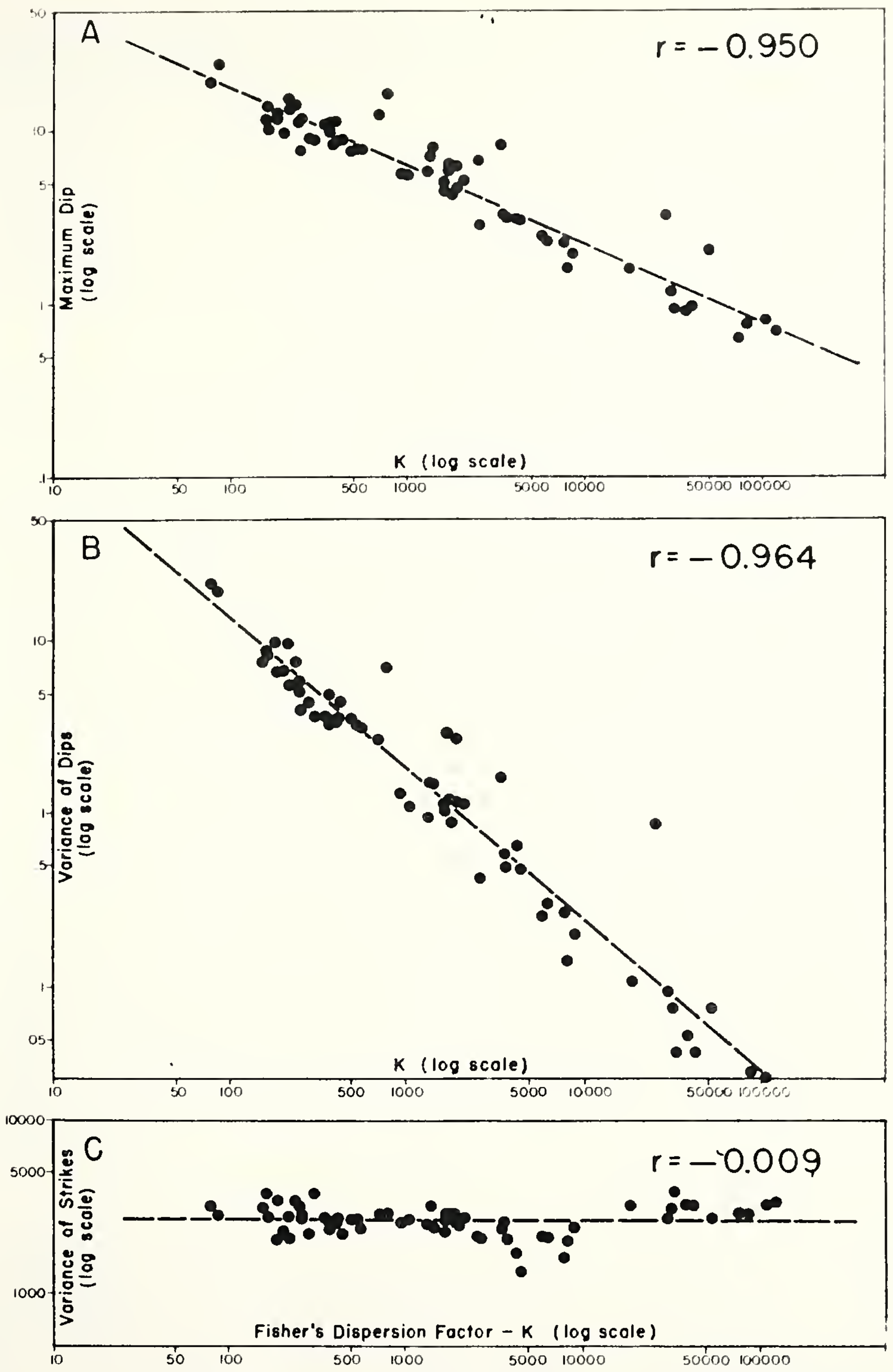
FIGURE 15. EFFECT OF TRIANGLE TYPE ON "K".

TABLE 2

RESULTS OF PROGRAM VECTOR ANALYSES

Test Site Number	Terrain Type	Elevation Range (ft)	Roughness K	log K	Variability v (ft)
A. Turner and Miles Test Sites					
02393-1	escarpment	315	85	1.929	163.5
02393-3	escarpment	278	82	1.914	145.1
03022-1	hills	340	397	2.599	131.0
02487-1	hills	277	220	2.342	118.5
02039-2	hills	212	158	2.199	96.5
W-1	drumlins	183	222	2.346	78.3
02039-1	karst plain	166	723	2.859	57.2
02039-3	karst plain	170	1329	3.124	54.6
02393	plateau	81	1759	3.245	25.0
02393-2	ridge moraine and dunes	53	2892	3.461	15.3
02329-2	ground moraine	60	24664	4.392	13.7
02329-1	outwash plain	28	18024	4.256	6.6
02625-1	ground moraine	26	30044	4.478	5.8
B. Stone and Dungundji Site (subarea numbers are figure numbers)					
M-29	Boulder-free wadi	25.0	31	1.491	16.8
M-57	Pleistocene lake terrace	10.8	51	1.708	6.3
M-33	Micro-badlands	9.0	117	2.068	4.4
M-45	Sand-sheet	10.5	309	2.490	4.2
M-49	Complex dunes	8.7	161	2.207	3.9
M-53	Turret dunes	7.0	133	2.124	3.3
M-41	Playa drainage channels	5.3	233	2.367	2.2
M-37	Floodplain mounds	3.0	269	2.430	1.2
M-39	Floodplain ridges	2.3	189	2.276	1.0
M-35	Salt polygons	1.4	102	2.009	0.7
M-47	"Devil's Cornfield"	1.15	975	2.989	0.4
M-55	Playa	0.47	374773	5.573	0.084

(after Turner and Miles)



(after Turner and Miles)

FIGURE 16. RELATIONSHIPS BETWEEN "K" AND STRIKE AND DIP VARIABILITY.

values, the log K transformation is frequently useful. A terrain variability factor, v, defined as the range in elevations in feet of the sample site divided by log K, was also found to be a useful statistic. The variability values are large in "rough" areas of high relief and small in smooth areas of low relief.

3) Roughness values appeared independent of type of triangle used in the analysis. This is shown in Figure 15.
4) The roughness values are strongly related to measures of slope, such as log (variance of dips) and log (maximum dip), but not to direction of slope as shown by log (variance of strikes). These results are shown in Figure 16, where r is the linear regression coefficient which measures the slope of the regression line.
5) A filtering action causes the orientations of the triangular planar elements to become progressively poorer estimators of the true terrain roughness as the grid spacing increases. Thus the investigator must consider the effect of sample spacing on roughness estimators when performing this type of analysis.

The almost horizontal regression line resulting from analysis of log (variance of strikes) and log (K), shown in Figure 16-C, merely substantiates that this procedure does not take symmetry arguments into account. Variability factors obtained for typical terrain situations are used in this research to devise stratified terrain sampling techniques. This application is described later in the thesis.

Power Spectrum Analysis Procedures:- Power spectrum analysis procedures are currently being extensively investigated by earth scientists, [24, 87, 88, 90]. Results to date indicate several possibilities for these procedures, particularly as a classification tool.

The basic approach is to apply techniques previously developed by electrical engineers to analyze signals that are largely random in nature. If these procedures can be applied to geological data, which is definitely "noisy" in nature, it is hoped that greater insight can be gained into fundamental relationships masked by the noise. Early results show promise, [24, 87] and there is hope that these techniques may aid in determining the point where regional and local components are most effectively separated in regression analysis, a recurring problem in certain forms of regression procedures. No attempt was made to apply these techniques to this research, however.

Surface Comparison Procedures:- Many methods of quantitatively measuring the similarity of surfaces have been described in the geological and geographical literature. Little agreement exists on a single best method because as Miller [72] states; "The problem of divising quantitative standards for comparing contour maps is very complicated. Difficulties appear at the very onset, in asking just what is to be compared." Two broad categories of techniques can be distinguished.

In the first category are found techniques which utilize the coefficients of equations which describe the surfaces being compared. As described in the following section, regression techniques are an important and popular numerical surface analysis procedure; thus comparison of coefficients is a natural and suitable procedure in many cases. Merriam and Sneath [68] calculated a statistic termed "the taxonomic distance," from the standardized coefficients, and used it to measure the similarity of trend maps. Rao and Srivastava [89] computed a similar distance function. Miller [72] utilized graphical methods to compare coefficients.

In many cases the surfaces to be compared are empirical and are not amenable to description by comparatively simple equations. Comparison of these surfaces involves the second category of comparison procedures. Miller suggested a visual matching of two maps and recording of the transformations and rotations required to obtain a best fit. Mirchink and Bukhartsev [75] described a "structural correlation coefficient" to be calculated from the absolute values of any two surfaces at a series of equivalent locations.

Tobler [112] described a similar technique of "cross-correlation." The procedure required both surfaces be evaluated on identical regular grids. The calculation of the simple correlation coefficient by matching each grid value with its corresponding grid value of the other map gives a single number indicative of the similarity of the two maps. A value of plus-one indicates perfect correspondence, zero indicates no correspondence, while a value of minus-one indicates perfect inversion. Tobler suggested the technique be carried further to allow a limited shifting of one map with respect to the other. Computing the cross-correlation coefficient resulting from the comparison of each grid value on the first map with a grid value displaced any unit number of rows or columns on the second map allows the researcher to shift the two maps left or right, up or down; however rotations, except in units of 90 degrees, are not possible. The various cross-correlation coefficients may be plotted on a correlogram with the direct comparison value at the center and the various shifted or "lagged" correlations located at appropriate relative positions. According to Tobler such correlograms show any assymmetry or cyclicity in the similarities of the two maps.

Rao and Srivastava [89] compared two sets of data in five ways. Regression analysis was used to fit trend surfaces which were compared by analysis of variance techniques. Error measures of the various coefficients were compared. Comparisons were also made on the basis of root-mean square (RMS) error computations, calculation of a distance function similar to the Merriam and Sneath procedure, and through the use of serial and cross-correlation procedures. Their paper gives a good review of the various possible surface comparison procedures.

Regression Procedures:- Of all the numerical surface analysis procedures described or proposed, that of fitted regressions has been the most popular with earth scientists. Geologists, geophysicists, and geographers have sought trends from various types of spatial data and this quantitative technique was one of the first to be utilized for this purpose. In spite of considerable work in the area, it remains a topic of continuing research interest.

Regression procedures are greatly involved in statistical theory and procedures. In the following discussion, a basic understanding of statistics is assumed of all readers. Those interested in more thorough treatments of all aspects of statistics are referred to standard texts such as Dixon and Massey [22], or Ostle [84], and to Draper and Smith [23], for a lucid discussion of regression procedures. Reference is also made to two texts dealing with statistical applications to geology;

Miller and Kahn [73], and Krumbein and Graybill [56].

Two broad categories of regression procedures are recognized; the general linear model, and nonlinear models. The general linear model is of the form

$$Y = B_0 + B_1Z_1 + B_2Z_2 + \ldots\ldots + B_pZ_p + \epsilon \qquad (1)$$

where the Z_i can represent any function of the basic independent variables X_1, X_2, ..., X_k. Such a model is termed linear because it is linear in the parameters. Thus all the following are linear models.

$$Y = B_0 + B_1X_1 + B_2X_1^2 + B_3X_1^3 + B_4X_1^4 + \epsilon \qquad (2)$$

$$\log Y = B_0 + B_1(\log X_1) + B_2(\log X_1)^2 + \epsilon \qquad (3)$$

$$Y = B_0 + B_1/X_1 + B_2/X_1^2 + B_3/X_3^3 + \epsilon \qquad (4)$$

While such models can represent a wide variety of relationships, there are many situations in which a model of this form is not appropriate. Models which are not linear in the parameters are termed nonlinear models. Two examples of such models are:

$$Y = \exp\,(\theta_1 + \theta_2t^2 + \epsilon) \qquad (5)$$

$$Y = \frac{\theta_1}{\theta_1-\theta_2}\,(\epsilon^{-\theta_2 t} - e^{-\theta_1 t}) + \epsilon \qquad (6)$$

In these examples the parameters to be estimated are denoted by θ's rather than B's as used previously. The models (5) and (6) are both nonlinear in the sense that they involve θ_1 and θ_2 in a nonlinear way but are of different characters. Model (5) can be transformed into

$$\ln Y = \theta_1 + \theta_2t^2 + \epsilon \qquad (5a)$$

which is linear in the parameters. Thus model (5) is intrinsically linear since it can be transformed into linear form. However it is impossible to convert model (6) into a linear form without an approximation of some kind, such as a power series expansion, and thus it is said to be intrinsically nonlinear [23].

Nonlinear regression analysis has been investigated by geologists only to a limited extent [49]. A lack of definite information on the relationships between process and response variables in geologic systems delayed the consideration of such models.

Surfaces determined by linear regression models can be further subdivided into two types; trend surfaces and response surfaces. These differ from each other only in the complexity of the surface portrayed by the model. The term "trend" (i.e., trend surface) was defined by Grant [32] as that which "can adequately be described by a polynomial of low order." Since then the term trend surface has been extended to include double Fourier series expansions as well as the original polynomial expansion [38, 47, 48, 130]. When the polynomial expansion is used, trend surfaces are usually classified according to their "degree." The degree of an equation refers to the highest power of the polynomials found within it; thus the presence of any of the terms x^2, xy, or y^2 is sufficient to raise an equation to the second degree. Some writers alternatively classify trend surfaces as linear, quadratic, linear plus quadratic, etc., according to the powers of the terms included. Krumbein [54, 55] and James [48] have studied the properties of "coefficient spaces" and have classified Fourier series trend surfaces into "harmonics".

The division between trend surfaces and response surfaces is not clearly defined. Krumbein and Graybill state "the trend seldom extends above the fifth or sixth degree." Sampson and Davis [98] and Davis [19] refer to trend surfaces as "a variety of response surfaces....in which two independent geographic variables are used," and refer to response surfaces as "power-function regressions in which independent variables are geographic coordinates." They suggest that multidimensional response surfaces are possible, although their analyses have been restricted to four-dimensional response surfaces [19, 98]. Thus, their response surfaces correspond to the hypersurfaces of Harbaugh [36]. Response surface analyses have been used to study mineralogical changes within rock bodies [19, 86, 98], and oil gravity data [36].

The earliest regression applications involved simple polynomial expansions to determine regional (trend) components of geophysical data [32, 33, 51, 80, 83, 104]. On early computers use of orthogonal polynomials gave distinct computational advantages since they have the property of lower terms remaining constant as further terms are added. Under such circumstances fairly complex regression equations could be built up on small computers. Orthogonal polynomials require equally spaced data points however, and this restriction led to the development of ingenious techniques to transform irregularly spaced data [52, 73].

The advent of larger, faster, and more accurate computers allowed the implementation of matrix algebra techniques to the solution of large numbers of simultaneous equations[23, 56]. It became practical to recompute all parameters for each surface being fitted, to use nonorthogonal polynomials, and to remove most of the restrictions on data distributions. Several computer programs [78, 82, 114, 128] are available to fit polynomial trend surfaces. The Fortran IV program used in this research is an adaptation of a program developed by Johnson and Goodell

[50], and is described in detail by Turner [114]. A Fortran IV program developed by James [47] to fit double Fourier series trend surfaces was also adapted for use in this research.

Trend Surface Analysis Techniques

Trend surface analysis, as developed by earth scientists, represents a special use of regression procedures and of the statistical theory on which such procedures are based. In the usual case, regression analysis develops a mathematical model to explain certain observed characteristics found in data. The researcher is anxious to obtain a "good fit" of the model to his data. However in general a "total fit" of the model to the data, in which the model perfectly honors all observations, is neither desired nor obtained. Except in special cases, such a perfect fit would occur only if the model contained as many terms as there were observations. In addition to being complex, such "total fit models" are often unduly constrained and unrealistic.

In contrast, trend surface analysis, as used in this research, is based on a slightly different premise. Krumbein and Graybill [56] explain this as follows:-

> "Trend surface analysis may be defined as a procedure by which each map component is divided into two or more parts: some associated with the "large-scale" systematic changes that extend from one map edge to the other, and others associated with "small-scale," apparently non-systematic fluctuations that are superimposed on the large-scale patterns."

However the term "trend surface analysis" is frequently misused in the literature and on occasion complex "response surfaces" have been misnamed "trend-surfaces."

Figure 17 shows schematically the types of information that is obtained from a true trend surface analysis procedure. Two sources of information are available; the trend surfaces themselves, and the "residuals" which represent the lack of fit of the trend surface to the original data. The information obtained from both trend surfaces and the residuals is classified as either descriptive or interpretive.

Procedures for Trend Surface Description

The trend surfaces supply considerable descriptive information. The morphometry of the surfaces can be studied either by comparison of the coefficients or by graphical means. Graphical displays of the trend surfaces, such as contour maps, are valuable in visualizing their shapes and allow the researcher to describe them in qualitative, as well as quantitative, terms. Perhaps more important, however, is the statistical description of trend surfaces. Through the use of appropriate statistical techniques trend surfaces can be evaluated to determine their utility and reliability in describing the data.

Statistical Evaluation of Trend Surfaces

The precision with which a regression model represents the data can be measured by comparing the distribution of the observations about the regression model with their distribution about the mean. This latter value is called either the "sum of squares about the mean," or the "corrected sum of squares of the observations."

As shown in Figure 18 for the two dimensional case, some of the total variation of the observations about their mean can be explained by the regression line, but some remains unexplained because the actual

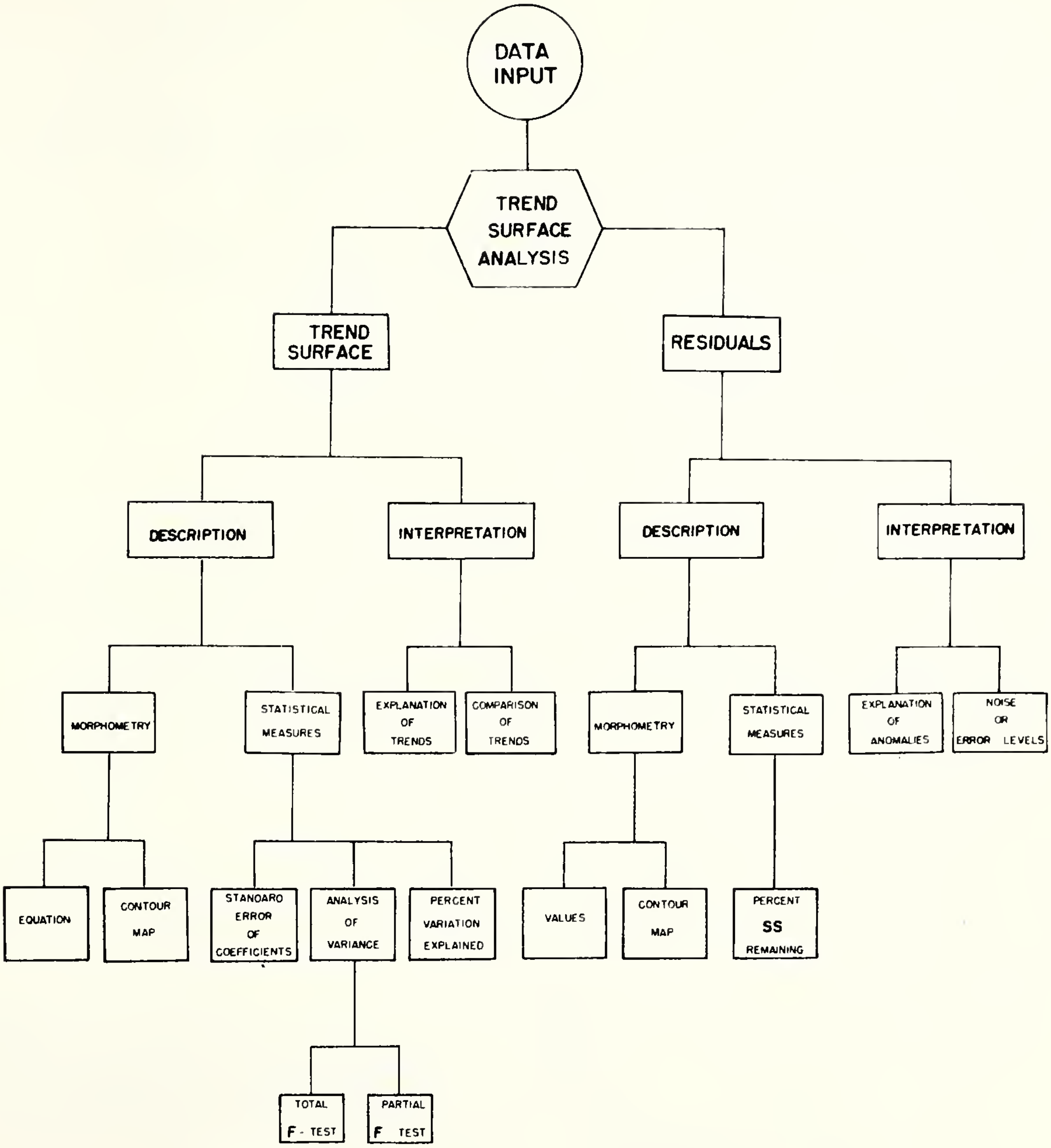


FIGURE 17. TYPES OF INFORMATION RESULTING FROM TREND SURFACE ANALYSIS

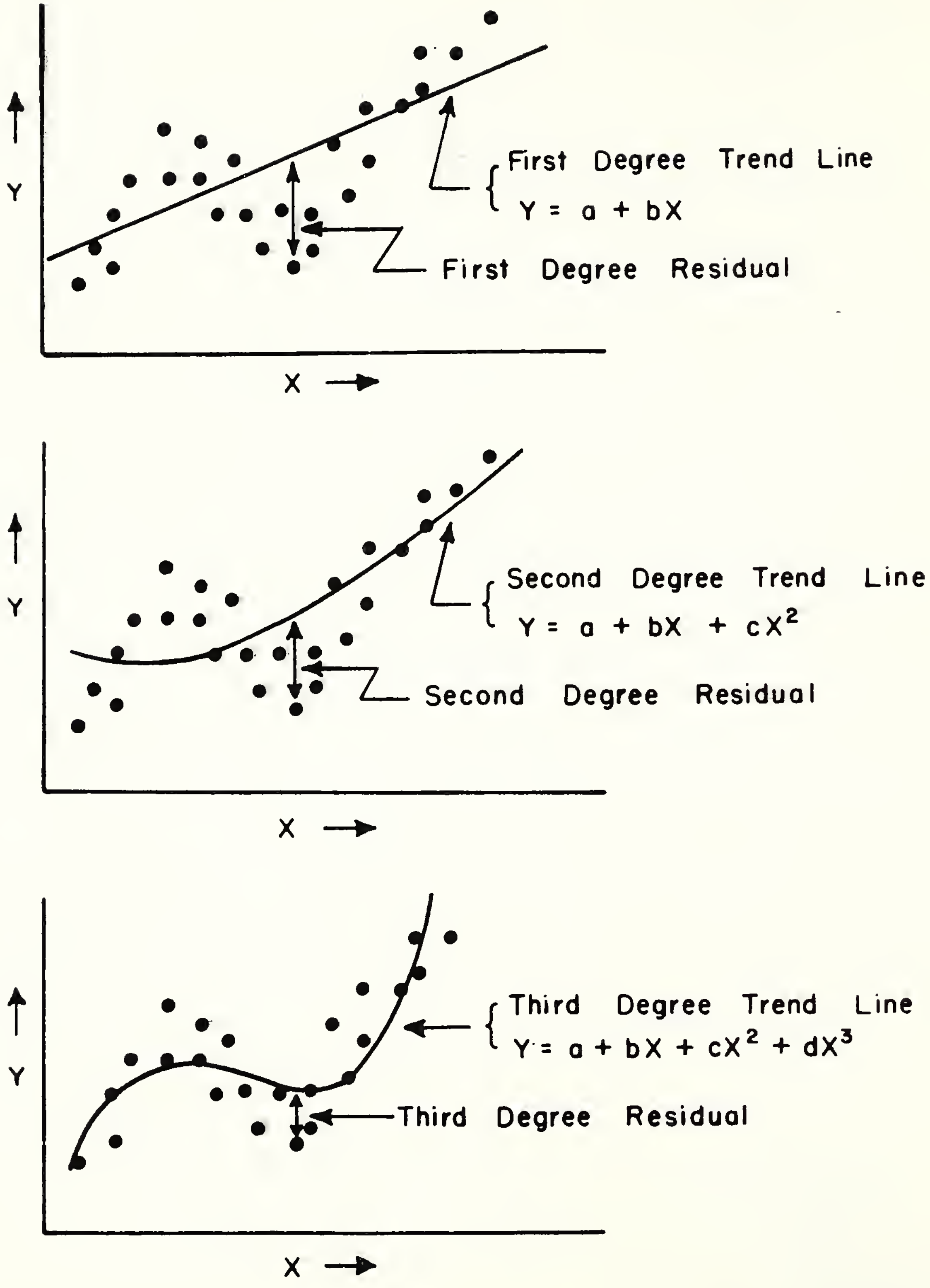


FIGURE 18. TWO DIMENSIONAL REGRESSION

observations do not all lie on the line. This can be summarized as:-

$$\text{Sum of Squares about Mean} = \text{Sum of Squares about Regression} + \text{Sum of Squares due to Regression}$$

If all the observations did lie on the regression line, it would "perfectly explain" the observations, the sum of squares about the regression would equal zero, and the sum of squares due to regression would equal the sum of squares about the mean. Thus the ratio of the sum of squares due to regression over the sum of squares about the mean is a suitable way of assessing the precision of the regression model. This ratio is frequently converted to a percentage and labelled "percent variation explained" [23]. It is numerically equal to R-squared, the square of the simple correlation coefficient. Analogous procedures can be performed for higher-dimensional cases.

The concept of division of sum of squares into components leads into analysis of variance procedures. The statistical theory and computations required by analysis of variance techniques are exhaustively discussed in many statistical textbooks [22,23,56,73,84]. The following is a brief outline of the procedure.

Initially, the number of "degrees of freedom" for each subdivision must be determined. These values are computed as follows: (1) the total number of degrees of freedom equals the number of observations, (2) correction of the sum of squares for the mean requires one degree of freedom, (3) each coefficient in the regression equation requires one degree of freedom, and (4) the remaining degrees of freedom belong to the deviations about the regression.

Each component sum of squares is divided by its appropriate number of degrees of freedom to obtain a value called the mean square. The mean square due to regression divided by the mean square due to the deviations about the regression will yield a statistic having an F-distribution.

If it is assumed that the mean squares of the deviation are the best estimators of the appropriate error variances, σ^2, for each regression, these "computed F-values" can be used to test the null hypothesis that the coefficients are not significantly different from zero. This is accomplished by comparing the "computed F-value" with a "tabled F-value" for 100 $(1-\alpha)$ percent in the $F(p,n-p-1)$ distribution; where α is the probability of the Type I error, p is the number of coefficients in the regression equation, and n is the number of observations. F-distributions are found in statistical references [22, 23, 84]. Any level of α may be selected by the researcher, as appropriate to his problem, however $\alpha = .05$ and $\alpha = .01$ F-distributions are the most commonly available and used. If the "computed F-value" exceeds the "tabled F-value", the null hypothesis, that all the coefficients are zero, is rejected, and it is assumed that the equation represents a significant effect with no greater a probability of α of being wrong. Such a test may for convenience be termed a "total F-test".

Analysis of variance techniques can be employed in another very important fashion to further test various regression models. The researcher is frequently interested in the relative worth of certain terms in his model. If some terms are found to have no value, then can be dropped from the model to produce a new simpler model. The importance of various terms is most easily determined by considering the increase in the regression sum of squares caused by including these terms in the model. This is known as the "extra sum of squares" concept and utilizes "partial or sequential F-tests" [23]. Any convenient breakdown to allow study of single terms or groups of terms having some special significance is allowable. For instance the significance of all first degree terms, or all second degree terms, is studied by handling them as groups.

The extra sum of squares concept involves the fitting of two regression models; one including the terms of interest, the other omitting them. Sums of squares due to regression for each model are determined. By subtraction, the "extra sum of squares" due to the inclusion of the terms can be obtained. The number of degrees of freedom associated with it equals the difference in the number of terms in the two models (i.e., the number of terms in the group being tested). The extra sum of squares divided by the proper number of degrees of freedom will produce a mean square value.

Once again, by assuming the mean square due to deviations is the best estimator of the error variance, σ^2, the ratio of mean squares yields a statistic having an F-distribution that can be used to test the null hypothesis that the coefficients in this group are not significantly different from zero. This is accomplished, as before, by comparing the "computed F-value" with an appropriate "tabled F-value." If the "computed F-value" exceeds the "tabled F-value", for any chosen level of α, the null hypothesis, that the coefficients in this group are equal to zero, is rejected, and it can be assumed that these coefficients are worthwhile.

These analyses rest on the assumption that the mean square of the deviations is the best estimator of the error variance. This is only true if the deviations (residuals) are random. If the residuals contain both systematic and random components, the mean square due to deviations will tend to be inflated and will no longer provide a good estimate of the random variation present in the data. This is a severe problem in trend surface analysis, since it appears intuitively likely that the residuals contain systematic effects if they are to contain local anomalies as well as "random noise effects."

This problem is recognized by more knowledgeable workers in this field. Krumbein and Graybill [56] suggest that the F-values be used only as indices for deciding on the relative merits of various trend surfaces. Draper and Smith [23] indicate the advantage of duplicate samples to aid in obtaining a better prior estimate of σ^2. These techniques have been carefully applied by McIntyre to the study of igneous rock compositions [79].

Analysis of variance procedures are very widely used to examine regression equations. Their popularity can be ascribed largely to their easy computation, particularly on computers when matrix algebra techniques are utilized to solve simultaneous equations for the coefficients, and to their seemingly powerful and useful capability of testing individual coefficients by means of partial F-tests. However many workers overlook or ignore the assumptions implicit in the use of these procedures; assumptions that are poorly met in some applications.

Draper and Smith [23] discuss other useful, but infrequently applied, statistics which can give the researcher additional guidance in analyzing his regression model. By far the most valuable of these procedures is the determination of confidence limits for the trend surface.

The determination of confidence intervals on trend surfaces and their interpretation in geological work is discussed by Krumbein [53,56]. From theoretical considerations, it can be shown that the width of the confidence interval varies with position along each independent variable. The computations are not convenient and must be repeated for many different geographic locations before the confidence limits of the entire map area can be determined. This accounts for the lack of use of this procedure. The geometries of the confidence limits become increasingly complex as the degree of the trend surface increases. This makes their interpretation increasingly difficult, and no doubt further inhibits their use.

Procedures for Trend Surface Interpretation

Examples of interpretation of trend surfaces are common in the geologic and geographic literature. Trend surface interpretation naturally follows their generation and description. Interpretation attempts to relate the trend surface to the processes being studied.

The simplest interpretation utilizes one trend surface to represent the major regional effect inherent in the data. Three dimensional trend surfaces have been applied in geomorphology to the study of raised shorelines [15], peneplains [27, 109], and homogeneity within physiographic provinces [61]. Geographers have studied population distributions [111] utilizing these procedures. Slightly more complex four-dimensional analyses, really response surfaces, have been used to interpret geochemical data [18], the composition of oil reservoirs [36, 37], and rock bodies [19, 86, 98], particularly granitic intrusions [21, 126, 127, 129].

Further interpretation is possible by comparing trend surfaces. Comparisons are possible between surfaces of differing complexity fitted to the same data, or between surfaces fitted to different data. Whitten [129] fitted trends of various degrees to a single set of data, then subtracted a low degree trend surface from a high degree trend surface and obtained maps of "secondary-trend components." Merriam and Harbaugh [67] identified structural discontinuities related to oil reservoir locations in Kansas through the study of trend surfaces fitted to different structural horizons.

In certain cases even comparatively simple trend surfaces closely fit the data. Such surfaces can form the basis of process-response models. Whitten [130] used trend surfaces in this way to simulate subsurface fold geometry. Relationships between ground water recharge and discharge rates and piezometric surface shape have been studied for an unconfined aquifer by Davis, Turner, and Melhorn [20]. In other cases however, trend surfaces do not closely fit the data. In some cases the fit has been greatly improved by subdividing the map area [21, 128]. When these techniques are successful, the interpretation is made that the data belongs to more than one population. Often this can have important implications.

Procedures for the Description of Residuals

There are comparatively few mathematical statistical procedures available to the study of residuals. Within the earth sciences emphasis is placed on interpretation of graphical residual plots, generally contoured residual maps, to the detriment of more rigorous mathematical testing. Graphical procedures depend greatly on the skill and experience of the researcher [110].

Draper and Smith [23] emphasize the need to plot and study residuals in any complete regression study, stating:-

> "In general residuals should be plotted in any reasonable way that occurs to the experimenter or statistician, based on specialist knowledge of the problem under study."

They describe several types of plots; most however being applicable only to two-dimensional cases.

Certain statistics have been suggested which will give numerical measures of certain residual characteristics. Anscombe [6] and Anscombe and Tukey [7] discuss these in detail. However, these procedures have not been widely applied, because, as stated by Draper and Smith [23]:-

> "....in practical regression situations a detailed examination of the corresponding residual plots is usually far more informative, and the plots will almost certainly reveal any violations of assumptions serious enough to require corrective action."

The presence of correlations among the residuals is probably the most serious problem facing the researcher wishing to carefully analyze them. In normal regression procedures, residuals represent "lack of fit," or error, and thus are expected to contain little or no correlation. In trend surface analysis however, considerable information is retained in the residuals, and correlation is to be expected. Recent studies by Anscombe and Tukey [7] suggest that correlation effects are minimized by the use of graphical procedures since "...the effect upon graphical procedures is usually negligible...". Under these circumstances it is perhaps not surprising that earth scientists normally study residuals graphically, by preparing residual maps.

Thomas [111] has carefully studied the characteristics of residuals, and the uses of residual maps in geographic research. He defined four types of residuals as follows:- (changes in notation have been made to conform with this report).

A) Residual Type 1 = $\hat{Z} - Z$

B) Residual Type 2 = $(\hat{Z} - Z)/Z$

C) Residual Type 3 = $\hat{Z}/Z$

D) Residual Type 4 = $(\hat{Z} - Z)/s$

where $\hat{Z}$ = estimated (trend surface value of dependent variable at any geographic (X and Y) location.

Z = observed (original data) value at the same geographic location.

s = $\sqrt{\text{residual mean square}}$ = estimate of $\sigma_{Z \cdot XY}$, the standard error of estimate.

In making these definitions, Thomas has reversed the sign convention used with residuals. Normally a positive residual occurs when the observed value is greater than the estimated value. In such cases Thomas' Type 1, 2, and 4 residuals are negative. His Type 3 residuals give values of less than one when the observed value exceeds the estimated (trend surface) value. It would perhaps be best if Thomas' residual definitions were changed to correct this disparity in the sign convention. However the characteristics of his residual types may be discussed without reference to their signs.

Thomas is unique in defining and analyzing different types of residuals. Unless specified otherwise, the term "residual" is universally taken to mean his Type 1 residual, the difference between observed and estimated values. Study of these four residual types indicates that Type 1 and Type 4 are closely related, as are Type 2 and Type 3.

Type 4 is merely a standardized form of the Type 1 residuals. Draper and Smith call Type 4 the "unit normal deviate" form of the residuals [23]. This form allows the researcher to quickly test the assumption that the residuals belong to a normal distribution with mean of zero. If this assumption is true, since 95% of the N(0,1) distribution lies between the limits (-1.96, 1.96) roughly 95% of the standardized Type 4 residuals should lie between the limits (-2,2). Occurrence of many values outside this range indicates the assumption of normality to be invalid. Occurrence of only a few values outside this range does not invalidate the assumption since the occasional value lying at some considerable distance from the limits (-2,2) is considered an "outlier" [5, 23]. Such outliers are peculiarities and indicate a data point which is atypical of the bulk of the data. Thus Type 4 residuals serve to emphasize unusual occurrences. Outliers should be carefully investigated, and should only be rejected if their occurrence can be traced to operator errors or equipment malfunctions [5].

The Type 2 and Type 3 residuals are both dependent on the ratio of the computed and observed values. As such they tend to produce map patterns which differ from those produced by Type 1 or Type 4 residuals. Thomas suggests that the use of such "ratio-residuals" may suggest additional model variables which are ratios.

Procedures for the Interpretation of Residuals

The interpretation of residual maps generally involves the graphical location of groups of positive or negative residuals, and the explanation or interpretation of the presence of such non-average areas.

Rockaway and Johnson [97] fitted trend surfaces to observed ground water levels and interpreted areas of high positive residuals as having above average ground water reserves. Allen and Krumbein [4] utilized residual maps to interpret heavy mineral percentages in a certain rock stratum. As a result of the residual patterns they defined a secondary "streaming action" which served to modify the overall regional patterns at the time of formation of the rock layer. Other workers [16] have utilized residual maps in studying mineral grain size distributions in eastern England. The large residual values were interpreted as being due to periglacial sorting processes.

Merriam [66, 67] utilized residuals extensively in interpreting Kansas rock structures. He was able to show how the Lost Springs oilfield was associated with local structural irregularities. Residual interpretations have also been applied in the analysis of granitic intrusions [125].

Most of the geological interpretations of residuals have utilized them as measures of geological heterogeneity. Hypotheses have been developed to explain these heterogeneities in purely qualitative terms. Thomas [111] suggested a more statistically based approach. He suggested that residual maps be used as tools:

1) to develop new hypotheses, and to identify and include new variables into improved regression models
2) to establish or modify regional boundaries of study areas
3) to identify and select specific unit areas in which to conduct field investigations.

Thomas gives examples of each of these applications. However they have not been broadly applied to date.

Computer-Generated Graphical Display Procedures

Graphical displays of three-dimensional data are an important and necessary adjunct to the successful application of numerical surface analysis procedures. Trend surface analysis in particular requires graphical displays of both the trend surfaces and the residuals.

During the initial phases of this study it became apparent that large numbers of three dimensional data displays would be required if a truly successful GCARS system was to be developed. The only feasible way to obtain these displays was to automate the display procedure; to program the computer to produce graphical displays of three dimensional data. Such procedures were not then available at Purdue, so the development of programs to produce computer-generated graphical displays of three-dimensional data was undertaken as part of this project.

The programs finally developed are described in detail elsewhere [114, 117]. They are based in part on routines developed by the Department of Geography, University of Michigan, Ann Arbor. However extensive modifications and translations from one computer language (MAD) to another (FORTRAN IV) were required before any programs were suitable for operation. Ultimately an integrated series of programs was developed to utilize both the standard character printer and the more specialized CALCOMP digital-incremental plotter.

Display System Characteristics

Use of the character printer has several advantages over the CALCOMP plotter, particularly in the initial stages of a study. First, the graphical output produced on the printer is produced as part of the regular job output, and is available concurrently with the analysis. Second, the printer is economical to operate and relatively fast (600 to 1200 lines per minute). Third, because the printer is an "on-line" device it does not require the use of special magnetic tapes, which are needed when the "off-line" CALCOMP plotter is used, thus reducing the chance of human error. Finally, printers are much more widely available than are specialized graphical display devices, such as the CALCOMP plotter.

Use of the specialized graphical display devices is justified when plots of superior quality are required. The resolution of the printer is limited by the line and character spacing. Since these are unequal, distortion may occur; although this can be avoided by careful planning of the display scale. In contrast, the plotter has no distortion and a resolution governed by its step size. In the model used in this research the step size is 0.01 inch, thus it can produce pen and ink drawings suitable for inclusion in reports.

While all digital-incremental plotters are much slower than the character printers in producing a completed display, one class of specialized equipment is as fast or faster. This is the cathode ray tube (CRT) display device, which typically has a display time of less than a half a second. Purdue University obtained a CRT display unit (a CDC model 250) as part of their new CDC 6500 computer system. Problems in software development have prevented the utilization of this device, which has not yet been made available to computer users.

The graphical display programs were designed to be easily compatible, allowing the preparation of working drawings on the more economical printer, while the final drafting of selected displays was performed on the plotter.

Methods of Surface Representation

The common methods of graphically displaying three dimensional data are:

1) perspective or isometric views of a surface
2) three-dimensional histograms
3) contour (isopleth) maps
4) choropleth maps.

The present work utilized both isopleth and choropleth maps. Development of truly satisfactory isometric or three-dimensional histogram displays involves more complex programming. Routines to perform these functions are under development and are to be integrated into the GCARS system at a later date.

Benefits and Limitations of Machine-Generated Contour Maps

Contouring may be performed in a variety of ways; extremely literal, extremely interpretative, or a compromise between the two [46]. The results obtained are dependent on the method used to interpolate between points of known value. Most computer-generated maps, including those developed in this study, give literal contours. Some attempts have been made to modify this literal interpretation to favor certain predetermined directions [116]. However in the general case, computer-generated contour maps are not "unbiased", as is often believed by the unwary, but are in fact strongly and consistently biased toward literal interpretation of the data.

As a consequence, computer-generated maps are not equally suitable for all applications. The speed of their production is often a great advantage. They are extremely useful as "quick-look" maps to give the researcher a general idea of his data, or the check the validity of data. Furthermore, since all computer-generated maps are made consistently, they can be used for comparison purposes. Human contouring of several data sets inevitably involves some learning processes which introduce an uncertain and subtle bias into the results, thus rendering comparison of maps difficult. In contrast, the computer does not "learn" from one data set to another, but handles all uniformly.

Minimum Path Analysis Procedures

Network analysis is a useful tool of operations research [40]. Minimum path analysis, the finding of the "shortest" route through a network, in terms of distance, time, or cost, is merely one application of network analysis. Often considered an extension of linear programming techniques, minimum path analysis may be considered a simplified form of dynamic programming since it contains a stagewise solution of a problem. It is most easily described in the terminology of the theory of graphs.

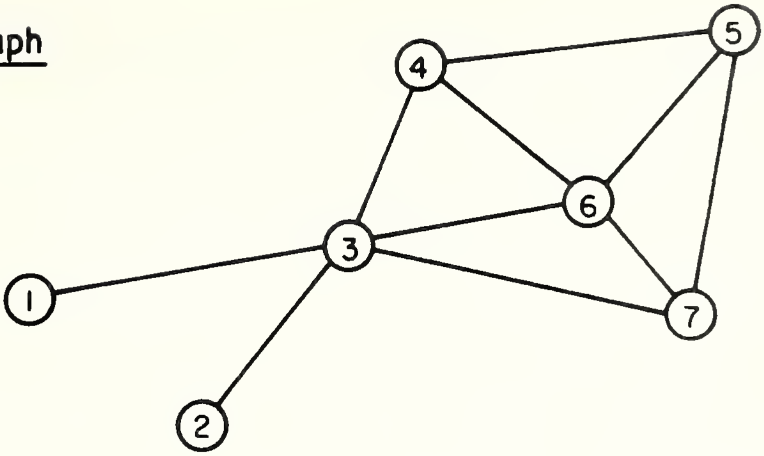
The Theory of Graphs

This section is partly based on a discussion of graph theory, network analysis, and dynamic programming by Hillier and Lieberman [40], to whom the reader is referred for additional information.

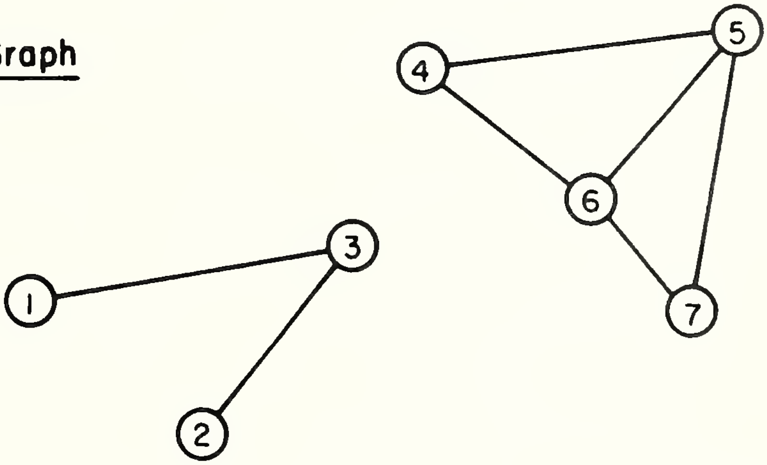
A graph consists of a set of junction points called "nodes", with certain pairs of the nodes connected by "links" (or "branches"). Figure 19 shows examples of graphs; the circles represent nodes and the lines represent links. A "network" is a graph containing a flow of some type in its links. Thus a series of roads can be considered a network consisting of nodes (intersections), links (roads), and flows on the links (traffic).

A series of links joining two nodes i and j is called a "chain"; if a direction of travel along the chain is included it is a "path". Thus

A) Connected Graph



B) Disconnected Graph



C) Tree Graph

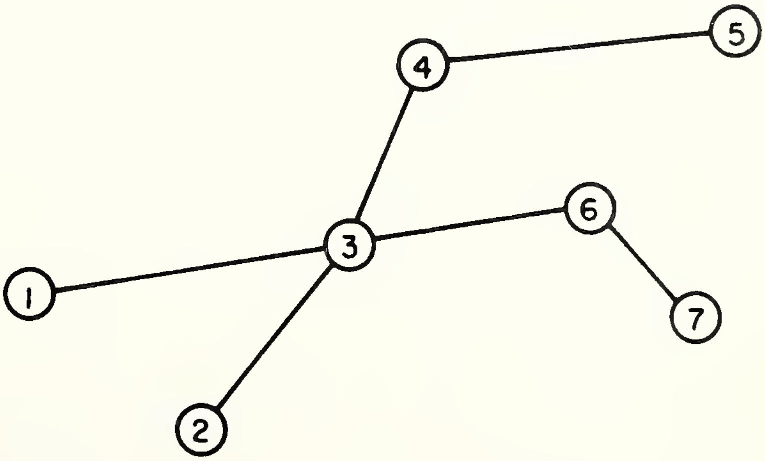


FIGURE 19. GRAPH DEFINITIONS

in Figure 19-A the links (1-3), (3-6), (6-5) form a path from node 1 to 6, the same links in reverse order form a path from node 6 to node 1, and together these two paths form a chain. A chain connecting a node to itself is called a "cycle;" for example links (3-6), (6-7), (7-3) in Figure 19-A.

A graph is called a "connected graph" if there is a chain connecting every pair of nodes. Figure 19-A shows a connected graph; but it is not if links (3-4), (3-6), and (3-7) are removed (Figure 19-B). A "tree" is a connected graph containing no cycles. Figure 19-A forms a tree if links (3-7, (4-6), (5-6), and (5-7) are removed (Figure 19-C). A tree is the minimum connected graph and will have (n-1) links, where n is the number of nodes.

A link is said to be "oriented" or "directed" if there is a sense of direction attributed to the link with one node being an origin and the other a destination. The "capacity", or "resistance," or "value," or "length" of the link is a measure of its ability to pass a flow in a specified direction. It may be measured in terms of time, cost, distance, etc., as applicable to the problem at hand. Vodrazka [120] terms links in which the capacity in one direction equals the capacity in the opposite direction "undirected" links.

Graphs may be specified by a "link table" in which each directed link is described by its origin node, its destination node, and its associated capacity. In the case of undirected links two entries are necessary in the link table, one covering movements from n_i to n_j, and the other movements from n_j to n_i.

Classification of Minimum Path Algorithms

A network composed of a finite number of nodes and links must have a finite number of paths connecting any two specified nodes. At least one of these paths is a "minimum path". Such a minimum path can be discovered by trial and error; however a more efficient computational procedure is desirable. A number of minimum path algorithms have been proposed to fill this need [25, 44, 45, 74, 76, 100, 101, 131]. Two categories of algorithms have been identified, matrix algorithms and tree-building algorithms. These reflect the two basic computational approaches that have been utilized.

Matrix algorithms simultaneously determine the shortest route between all node pairs in the network. Several of these algorithms have been suggested [25, 44, 45, 74, 100, 101]. However, these algorithms require large computer memory storage requirements, which increases rapidly for large networks. Mills [74] in describing the "most elegant and efficient of the matrix methods" states that the simultaneous storage of $2n^2$ variables is required, where n is the number of nodes in the network. Vodrazka [120] notes that, according to this formula, a network of 500 nodes would require 500,000 computer memory locations. Time requirements for the solution of a problem by the matrix methods increases approximately as the cube of the number of nodes [74]. Recent work has been devoted to shortening the calculations [44, 45, 74].

Tree-building algorithms have also been extensively studied [76, 131]. These are able to find the shortest paths from a single source node to each of the other nodes in the network. The set of all these paths forms a tree graph, hence the name of the algorithms. This process must be repeated until all nodes have been source nodes before all the information supplied by a single matrix method calculation is obtained.

Two well known tree building algorithms are the Moore algorithm and the Road Research Laboratory (RRL) Algorithm. The Moore algorithm was first proposed in 1957 [76] and has since been used extensively by the Bureau of Public Roads [12, 13]. The operation of this algorithm is described by Martin [65] and Vodrazka [120]. The RRL algorithm was developed by the Road Research Laboratory of the British Government's Department of Scientific and Industrial Research [131]. The operation of this algorithm is described in detail by Martin [65], its theoretical basis is explained by Hillier and Lieberman [40] who summarize its operation as consisting of the following two steps:-

1) Connect source node to nearest node.
2) Identify the unconnected node that is closest to any connected node. Repeat this until all nodes have been connected.

This procedure automatically generates the minimum path tree connecting the specified source node to all other nodes in the network. No iterations are required. This is in contrast to the Moore algorithm which does require some iterations [76, 65]. Because of this direct solution characteristic, the RRL algorithm can be modified to find a minimum path between a single origin and destination. This is accomplished by testing each entering node to see if it is the required destination. The calculation is stopped as soon as the destination node is reached. When the only information desired is the single minimum path from one origin to one destination considerable savings in computation time are possible by computing only a partial tree.

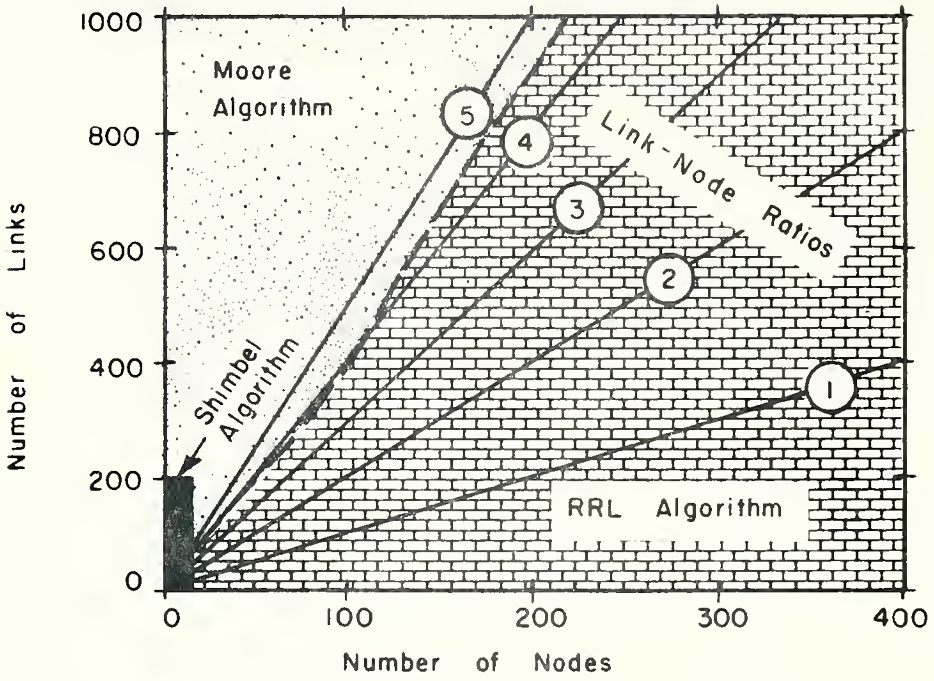
Comparison of Alternative Minimum Path Algorithms

Martin [65] compared four different algorithms. Two tree-building algorithms, the Moore and the RRL algorithms, were compared to each other and to a matrix algorithm, the Shimbel algorithm [100, 101]. In addition, calculations to determine a single minimum path were performed by a modified version of the RRL algorithm and a fourth algorithm developed by Martin. This latter algorithm was called the Origin and Destination (O and D) algorithm, and is a special formulation of the RRL single path algorithm. It simultaneously computes two partial trees, one from the origin and one from the destination, which meet to form a single minimum path.

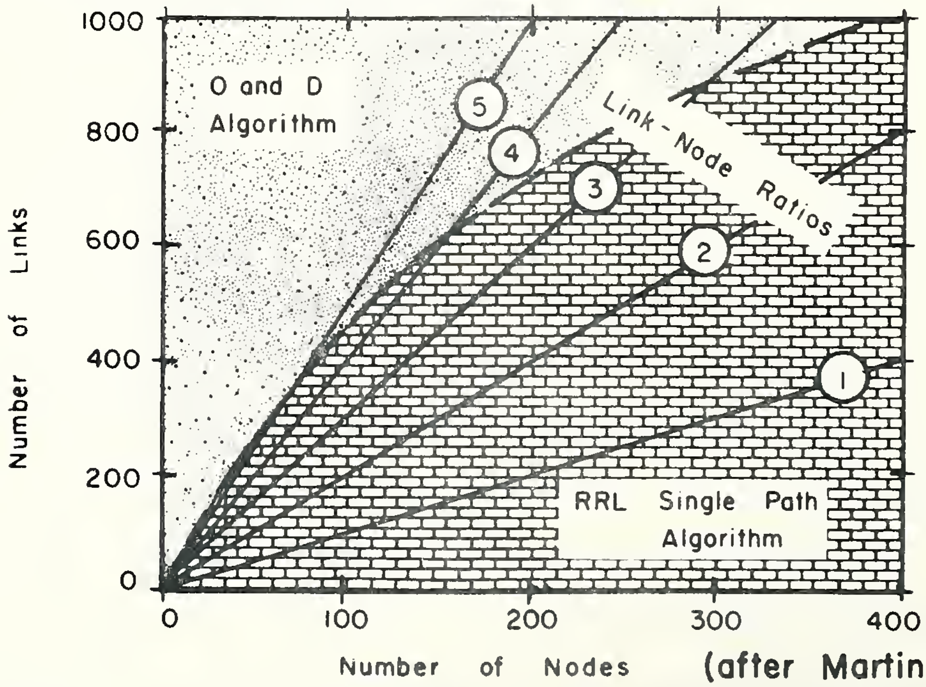
All algorithms were programmed in FORTRAN II and tested on two different computers; an IBM 1620 and an IBM 7090. Six different networks were analyzed by each algorithm. These networks were of different sizes and had different link-node ratios. Martin was able to prepare charts, reproduced in Figure 20, which show the algorithm giving the shortest computation time for various network link-node ratios and sizes. His networks were small by the standards of this research. His smallest contained only nine nodes and twenty-four links; his largest, 366 nodes and 990 links. Martin concluded that no difference occurred in the ranking of the algorithms on the two computers.

Considerations other than computation time were evaluated. Most important of these was the amount of information storage required. Martin discovered the O and D algorithm to require about double the storage of the Moore or RRL algorithms; the Shimbel algorithm storage

A) Results for Computation of Trees



B) Results for Computation of Paths



(after Martin)

FIGURE 20. COMPARISON OF MINIMUM PATH ALGORITHMS BASED ON COMPUTATION TIMES.

requirements exceeded the others by 10-20 times, depending on the network. Martin concluded:- "The Moore and RRL algorithms are convenient to use, the O and D less convenient, and the Shimbel rather inconvenient."

Special Applications of Minimum Path Analysis

Vodrazka [120] utilized the Moore algorithm to study and classify the state highway system of Indiana. Traffic volumes were assigned to highway links throughout Indiana and in parts of adjoining states. As a result an extremely large network was developed, containing 4582 nodes and 6345 links [120].

Such a large network could not be processed all at once on the computer since it greatly exceeded the available memory. Vodrazka [120] thus developed a method of partitioning the network. Ultimately six subnetworks were utilized. A decomposition algorithm was developed which first divided the original network into a series of parts, separated by border zones. A series of link tables were prepared which included all links between border nodes and subset nodes. Inter-connected border nodes were included in only one appropriate link table. A complex series of applications of the Moore algorithm to various subset link tables was necessary in order to discover the true minimum paths, because they may cross and re-cross border zones many times. Vodrazka outlines these procedures in detail.

The current research has restricted its analyses to networks which can be analyzed without decomposition. However it is recognized that many practical studies will involve large networks which will require decomposition before they can be solved. Integration of Vodrazka's decomposition techniques into the GCARS system will allow for the analysis of such large networks.

Ayad [8] utilized a version of the RRL single path algorithm. Ayad modified the algorithm so he could discover, not only the minimum path between a selected origin and destination, but a second-best distinctively different or alternate route between the same node-pair, then a third-best alternative, and so on for as many alternatives as he desired, or until constrained by the size of the network. This technique for generating alternative paths is important to the successful operation of the GCARS system.

Ayad wished to determine alternate routes "in a systematic and efficient way." He defined the determination of alternate routes as "the selection of distinct corridors (of travel) within the study area." Obviously a minor difference between two paths did not justify their consideration as alternate routes; rather the alternates should be unique over "considerable portions of their lengths." The alternate routes would have to share limited segments of the network in the vicinity of their terminals, otherwise they might be unduly constrained in reaching their specified origin or destination. These considerations led Ayad to propose the following process:-

1) The minimum path between a specified node-pair is determined by an appropriate algorithm (the RRL single path algorithm).
2) This minimum-path is checked against a level of service criterion, and, if it passes, a central percentage of this path is removed from the network description. Only control sections, such as bridges or tunnels are exempted.
3) The minimum path algorithm is re-applied to the reduced

network to find a new "minimum path" which will be the second-best alternate. This second-best route is compared to the level of service criterion.

4) If the second-best alternate passes the level of service test, a central percentage of this route is removed (any control sections excepted) and the minimum path algorithm is re-applied.

By this technique third, fourth, fifth-best, etc. alternate routes are determined and the process continues until the level of service is no longer met, or the network is fully utilized.

Links can be "removed" from the network by assigning arbitrarily extremely high resistance values to travel on those links (in terms of cost, time, volume, etc.) so that they become extremely unattractive in further manipulations.

Ayad realized that the percentage of central links removed, in other words the "percent overlap" allowed, was likely to greatly affect the results obtained. If the overlap was too great, alternate routes would be hardly distinguishable; if the overlap was too small, the alternatives would become unduly constrained in trying to reach their terminii.

After experimenting with various percentage overlaps, Ayad was able to conclude that overlaps which exceed 15 percent of the total route lengths tend to preclude development of distinct alternates. He found little change occurred in the character of the alternates when the overlap at each end of a route ranged between three and ten percent. He finally suggested that a seven-percent overlap at each end was probably optimal. These conclusions are of course only valid for Ayad's networks. They probably can be applied to networks having similar link-node ratios.

The current research uses a rectangular grid network having a link-node ratio of close to 4:1, which is similar to Ayad's grid-like street networks.

Ayad found that some limit should be placed on the total number of alternate routes chosen. Otherwise obviously unsuitable paths would be found, at a waste of computer time. He considered a number of alternative restrictions and found that a value of 1.75 times either the travel time of the total distance of the first path effectively separated the useful from the trivial alternatives. He did not believe a limiting total-number criterion to be suitable, perhaps because the total times or lengths of his paths increased quite rapidly from their minimum values. However, in the current research the optimum solutions generally are not as sharply defined. Thus large numbers of alternatives are generated, unless a limiting criterion is applied to specify the maximum number of alternatives desired. For this project the minimum path analysis continued until either seven alternatives were generated, or until the latest path total equalled or exceeded twice the first path total.

CHAPTER IV

METHOD OF INVESTIGATION

The Generalized Computer-Aided Route Selection (GCARS) System was described in Chapter I and Figure 4 (page 16). The methods of investigation discussed in this and subsequent chapters were used to develop and test a prototype GCARS System. Accordingly, the results obtained should not be considered as answers to any actual highway location problem currently under investigation by the Indiana State Highway Commission.

The method of investigation parallels the structure of the GCARS System. The investigation can be broken down into eight steps which can be compared to the data preparation, search, and selection activities of the GCARS System. This is shown in Table 3. The first three steps, the data preparation activity, are discussed in detail for both test areas in this chapter. The later steps are summarized in this chapter and described in detail in chapters five and six.

Identification of Highway Location Factors

Natural and man-made conditions, and physical and economic constraints affecting the selection of highway locations are termed "highway location factors." The identification of appropriate highway location factors for any particular analysis is a complex process dependent on:-

1.) the level of analysis within the highway planning hierarchy

2.) conditions inherent within the area of interest

3.) the personal judgment of the planning engineer.

For example, as discussed previously (see page 24), Alexander and Manheim [1] defined 26 factors they believed important at the route level of the highway planning hierarchy for a test area in western Massachusetts. However, the factors chosen, and the meaures selected to describe each, undoubtedly would have changed if the level of the analysis, the test area, or the planning engineers were changed.

At any level within the highway planning hierarchy, two groups of highway location factors can be distinguished. The first group includes those factors which may be used to define a preliminary set of possible alternatives. Topography, soil, geology, and foundation condition, present or future land use and value, and present or future travel demand are examples of these factors. Since they can be studied without reference to any pre-selected alternative, these factors are called "route-independent factors."

Once a preliminary set of alternatives has been developed, a second group of factors can be identified. These factors are used to refine the preliminary alternatives to produce a final set of alternatives. This second group of factors includes all the so-called "user costs and benefits," as well as many aesthetic, social, and economic considerations such as the disruption of communities or facilities, or the merits of alternative designs for elevated, depressed, or at-grade highways. These factors cannot be studied except with reference to a preselected alternative, and therefore are called "route-dependent factors." The five step sequence in the generation of alternatives is shown in Figure 21.

TABLE 3

THE METHOD OF INVESTIGATION

Activities*	Procedures	
	Step Number	Description
Data Preparation	1	Define route-independent factors and select or prepare graphical measures of each factor.
	2	Define sampling procedures.
	3	"Digitize the data" - convert graphical measures to numerical measures.
Search	4	Transform numerical measures to values by applying a suitable value function or rating scale.
	5	Check values for accuracy and lack of bias through the use of trend surface analysis procedures.
	6	Transform values to utilities, and construct utility networks on single or combined utility surfaces.
	7	Generate single and multiple factor alternatives by repeated application of minimum path analysis procedures.
Selection	8	Evaluate generated alternatives and reorder if necessary to reflect route-dependent factors.

*Activities described on pages 15-19 and Figure 4 (page 16).

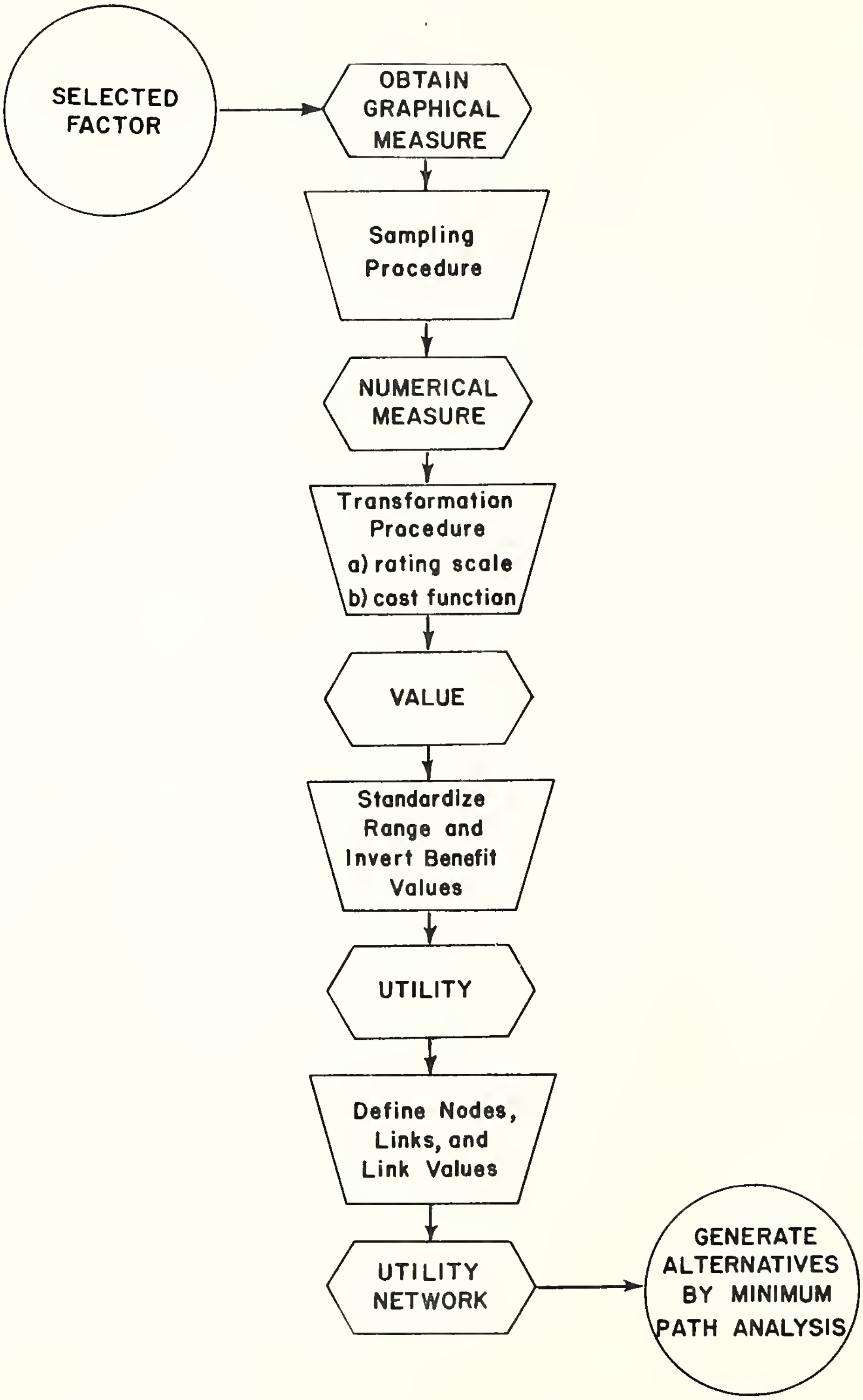


FIGURE 21. DATA ANALYSIS SEQUENCE.

Many route dependent factors cannot be described except at the lowest levels of the highway planning hierarchy. For instance, it is extremely difficult, if not impossible, to quantitatively evaluate the disruptive costs or aesthetic values associated with a corridor. Consequently in the upper levels of the highway planning hierarchy where the GCARS System is expected to be used, only generalized values can be assigned to most route-dependent factors.

Factors Studied by the GCARS System

The GCARS System generates alternatives primarily on the basis of route-independent factors. The factors studied in this investigation were:-

1.) an Earthwork Cost factor
2.) a Pavement Construction Cost factor
3.) a Right-of-Way Acquisition Cost factor
4.) Service Benefit factors.

The earthwork cost and pavement construction cost factors can be considered as the route-independent construction cost factor because route-dependent factors such as interchanges, bridges, or other structures are not considered. The pavement construction cost factor measures the ease with which a good-quality, long-wearing, non-frost susceptible roadway base can be constructed knowing the present soil and drainage conditions. This factor is likely to have greater significance for highways constructed with flexible pavements, since the design of adequate flexible pavements is dependent on pre-existing conditions to a greater degree than is the design of rigid pavements. However, either type of pavement will have better performance on better subgrade materials.

The service benefit factors include measures of present or future traffic demands and non-duplication of presently existing facilities.

The GCARS System does not ignore the route-dependent factors. The alternatives generated are a preliminary set of alternatives and should be examined and compared through the use of certain route-dependent factors. Generalized values of these factors can be used to re-order the alternatives previously selected. This analysis occurs during the selection activity at each level of the highway planning hierarchy.

Selection and Description of Test Areas

Two test areas within the State of Indiana were used in this study. Figure 22 shows their locations. The large southern test area was selected for regional studies, typical of the Band and Corridor levels of the highway planning hierarchy. The area contains a variety of terrain and foundation conditions since it covers several of Indiana's physiographic subdivisions as defined by Malott [62, 99].

Although this southern area includes several medium sized towns and cities ranging in population from 20,000 to 50,000, little detailed information was readily available to the author for any of these population centers. Information regarding land values, population densities, and trip ends was believed necessary when more detailed location studies at the Corridor or Route levels of the highway planning hierarchy were to be performed near such urban centers. In order to evaluate the procedures necessary for such studies, while avoiding expensive data collection, a suitable urban area for which detailed information was available had to be found.

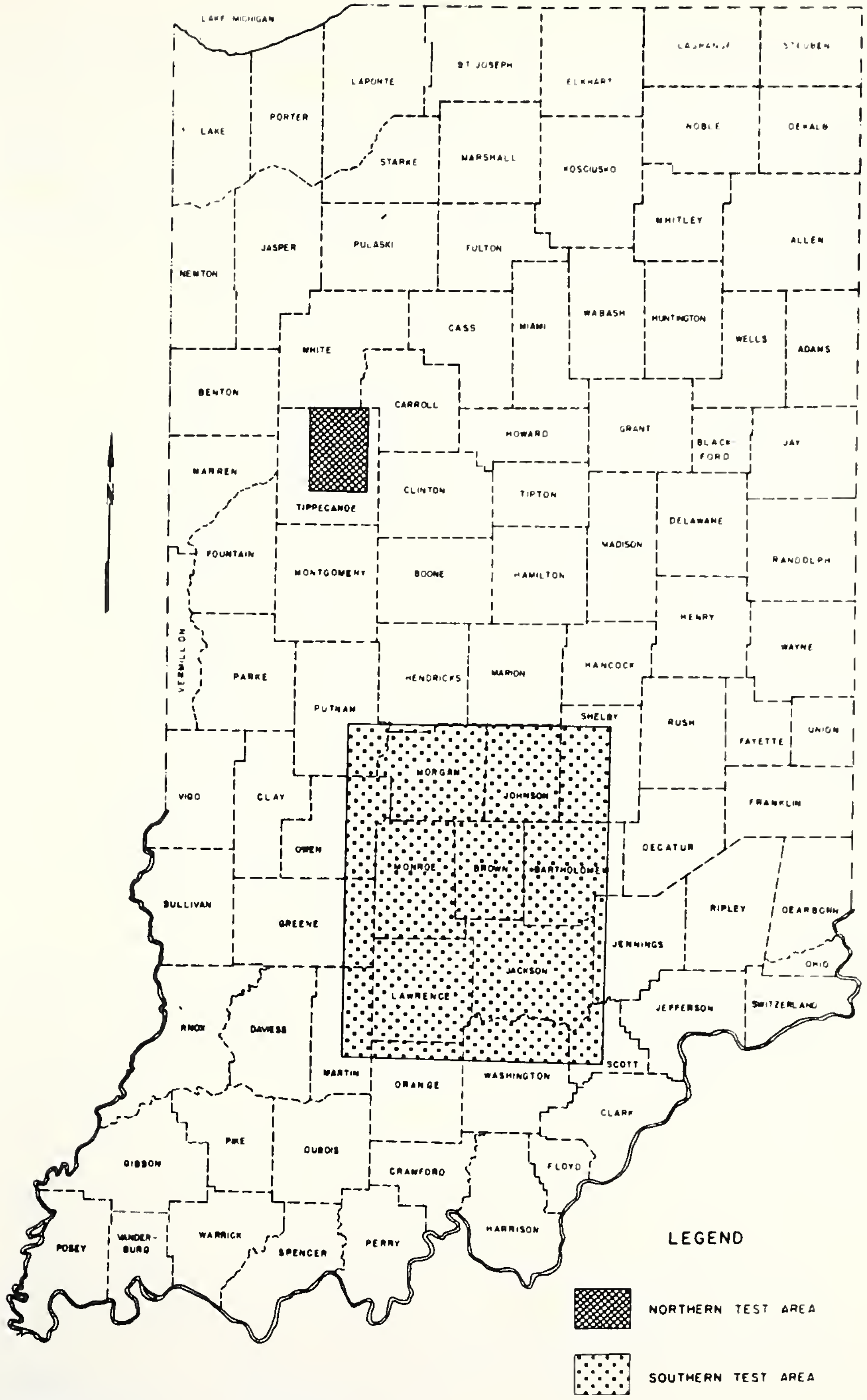


FIGURE 22. LOCATION OF TEST AREAS.

The cities of Lafayette and West Lafayette form a medium sized urban area, for which ample data on land use, population, and trip distributions are available. Consequently a northern test area was chosen comprising about half the total area of Tippecanoe County centered about Greater Lafayette.

Description of the Southern Test Area

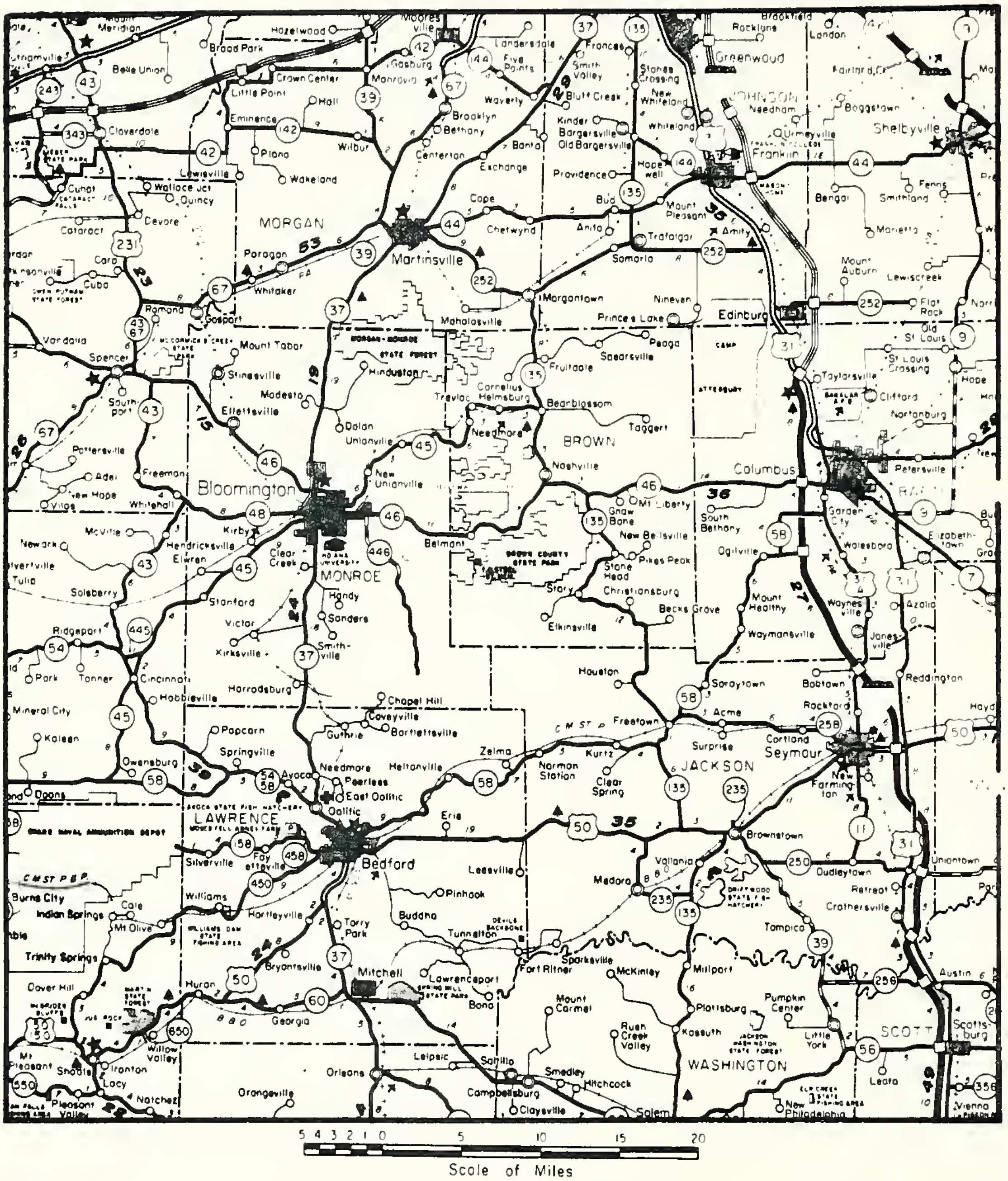
The southern test area lies south-southwest of Indianapolis and is approximately 55 miles wide and 68 miles long. It extends from Greencastle in the northwest to Shelbyville in the northeast and from Shoals in the southwest to Scottsburg in the southeast. The boundaries were defined to conform to the boundaries of the 1:24,000 scale 7½ minute topographic quadrangles. As shown in Figure 23, seventy-two of these maps lie within the study area. The area also covers part of four 1:250,000 scale topographic maps; these being the Indianapolis (NJ 16-2), Cincinnati (NJ 16-3), Vincennes (NJ 16-5), and Louisville (NJ 16-6) map sheets.

This area probably includes the greatest variety of topographic, geologic, pedologic, and cultural conditions displayed by any area of comparable size within the State of Indiana. As shown in Figure 24, it includes part of all of 16 out of a total of 92 counties within the state.

Figure 25 shows the general topographic features of the area. The great variety of topographic forms is emphasized by the presence of parts of six state physiographic divisions each having distinctive characteristics [62, 99]. This southern test area straddles the Illinoian and Wisconsin glacial boundaries, as shown in Figure 26. The south central parts of the area are bedrock controlled while extensive glacial deposits

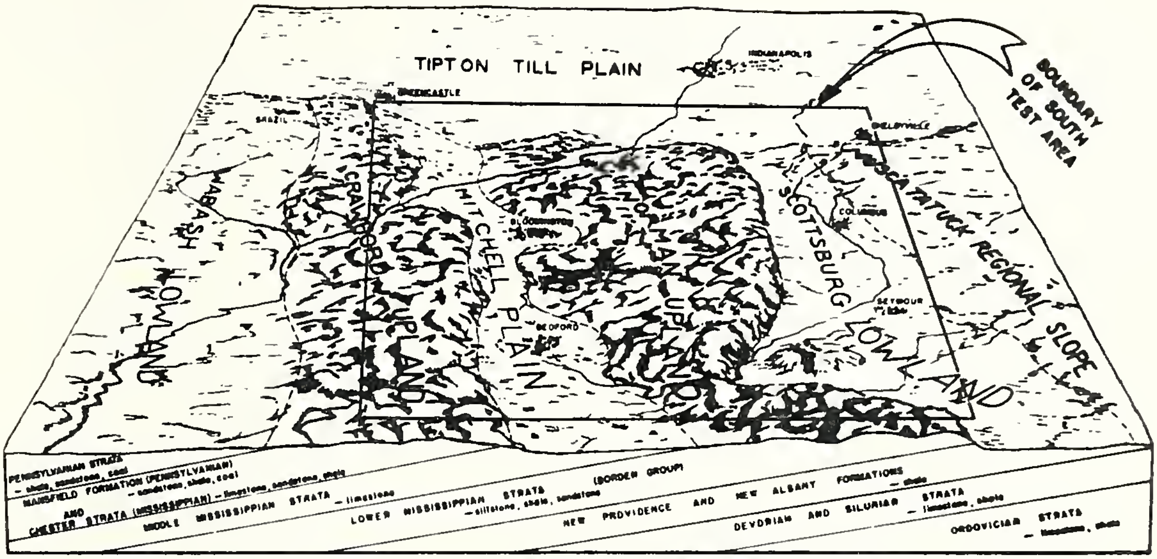
Cloverdale	Eminence	Hall	Mooresville West	Mooresville East	Bargersville	Greenwood	Boggstown	Shelbyville
Cataract	Quincy	Paragon	Martinsville	Cope	Trafalgar	Franklin	Marietta	Lewis Creek
Spencer	Gosport	Modesto	Hindustan	Morgantown	Bean Blossom	Nineveh	Edinburg	Hope
Freedom	Whitehall	Bloomington	Unionville	Belmont	Nashville	New Bellsville	Columbus	Elizabethtown
Solsberry	Stanford	Clear Creek	Allens Creek (S)	Elkinsville	Story	Waymansville	Jonesville	Azalia
Koleen	Owensburg	Oolitic	Bartlettsville	Norman	Kurtz	Brownstown	Seymour	Chestnut Ridge
Indian Springs	Williams	Bedford West	Bedford East	Tunnelton	Medora	Vallonia	Tampico	Crothersville
Shoals	Huron	Georgia	Mitchell	Campbellsburg	Smedley	Kossuth	Little York	Scottsburg

FIGURE 23. THE SEVENTY-TWO MAP QUADRANGLES (Scale 1:24,000) COVERING THE SOUTHERN TEST AREA.



Source:- Official Indiana State Highway Map

FIGURE 24. MAP OF SOUTHERN TEST AREA SHOWING TOWNS AND HIGHWAYS.


TIPTON TILL PLAIN
INDIANAPOLIS
GREENCASTLE
BRAZIL
SHELBYVILLE
BOUNDARY OF SOUTH TEST AREA
WABASH LOWLAND
CRAWFORD UPLAND
MITCHELL PLAIN
NORMAN UPLAND
BLOOMINGTON
BEDFORD
SCOTTSBURG LOWLAND
COLUMBUS
SEYMOUR
MUSCATATUCK REGIONAL SLOPE
PENNSYLVANIAN STRATA — shale, sandstone, coal
MANSFIELD FORMATION (PENNSYLVANIAN) — sandstone, shale, coal
AND CHESTER STRATA (MISSISSIPPIAN) — limestone, sandstone, shale
MIDDLE MISSISSIPPIAN STRATA — limestone
LOWER MISSISSIPPIAN STRATA (BORDER GROUP) — siltstone, shale, sandstone
NEW PROVIDENCE AND NEW ALBANY FORMATIONS — shale
DEVONIAN AND SILURIAN STRATA — limestone, shale
ORDOVICIAN STRATA — limestone, shale

SOURCE: — INDIANA GEOLOGICAL SURVEY GUIDEBOOK NO. 12.

FIGURE 25. PHYSIOGRAPHIC DIAGRAM OF SOUTH-CENTRAL INDIANA.

are found in the northern and eastern parts of the area.

As shown in Figure 25, the bedrock formations dip westward at low angles. The southern Indiana region was reduced to a peneplain in Tertiary time [62, 122]. In late Tertiary and early Quaternary time uplift of the area caused differential erosion of the various rock units. The continental glaciers covered the northern part of the area, while the meltwaters excavated entrenched valleys through the unglaciated regions in the south central part of the test area.

The Crawford Upland (Figure 25) lies along the western edge of the test area. It is a maturely dissected plateau sloping gently westward. A well integrated drainage system is deeply entrenched so that much of the area is in slope. The flat-topped interstream divides are mostly narrow. The area is probably the most rugged region in the State; local relief in excess of 300 feet is not uncommon [62,99].

A ragged poorly defined east facing escarpment, the Chester Escarpment, separates the Crawford Upland from the Mitchell Plain (Figure 25). The Mitchell Plain is a Karst plain, one of the best examples of this topography in the world. It is formed on a sequence of middle Mississippian limestones, several members of which are particularly susceptible to solution. As a result the plain is covered with sinkholes and other solution features. Over 1000 sinkholes have been counted in a square mile near Orleans in the southern part of the area [62]. The sinkholes may have a local relief of 30 feet. The Mitchell Plain also is crossed by a number of entrenched streams such as the East Fork White River, Salt Creek, and their tributaries, which serve to further increase the local relief.

To the east of the Mitchell Plain another area of hills is encountered, the Norman Upland (Figure 25). The Norman Upland is formed on the siltstones, shales, and sandstones of the Borden Group. It is an area of strong local relief with flat-topped narrow divides, steep slopes and deep V-shaped valleys. The concordant summit levels reflect the early Tertiary peneplain which is now greatly dissected. Much of this area is part of either the Brown County State Park or the Hoosier National Forest. Its eastern boundary is marked by a prominent escarpment, the Knobstone Escarpment. This escarpment rises some 500 feet above the lowlands to the east in the southern part of the test area, but gradually loses height and is finally buried beneath glacial deposits in the northern part of the area.

The lowland to the east is known as the Scottsburg Lowland (Figure 25). It is essentially a strike valley eroded on weak shale formations. However extensive glacial deposits partly fill the trough to depths in excess of 150 feet within the test area [99]. As a result of this infilling, the local relief is slight. Most is the result of recent erosion by present day streams along glacial sluiceways to form terraces; as for example along the East Fork White River, the major stream in the area.

The Scottsburg Lowland grades eastward into an area of similar local topographic conditions but with a marked westward slope, the Muscatatuck Regional Slope. The boundary between these regions is not well defined.

In the northern quarter of the test area the previously described bedrock regions become buried under progressively thicker glacial deposits and can no longer be distinguished. These glacial deposits belong to the Tipton Till Plain region (see Figure 25). This is an area of predominantly low to negligible relief. Local hilly or rolling areas exist along its southern border. These are end moraines of the Shelbyville morainic system.

Figure 26 shows the distribution of generalized engineering soil types found within this test area. This map was developed from a statewide engineering soils map prepared by Belcher, Gregg and Woods [10]. Because of the variety of geological conditions occurring in this region, twelve soil classes were mapped. Some of these are of glacial or glacial-fluvial origin; others are residual soils derived from the underlying bedrock; while a few are compound soil types consisting of thin glacial deposits overlying residual soils and bedrock.

Figure 24 shows the chief roads and principal communities within this area. Two north-south population corridors exist; one along the Scottsburg Lowland in the eastern part of the area and the other along the Mitchell Plain in the west-central part of the area. The intervening Norman Upland is unsuitable for agriculture or industrial uses and has tended to be a barrier between the two corridors. In recent years its importance as a recreational area has been growing steadily.

Land use activities were studied on the most recent available air-photo index mosaics obtained from the Aerial Photography Division, Agricultural Stabilization and Conservation Service, United States Department of Agriculture* for each county in the study area. Ten land use categories were identified. The results were compiled to form the map shown in Figure 27. Agricultural uses are concentrated in the Mitchell

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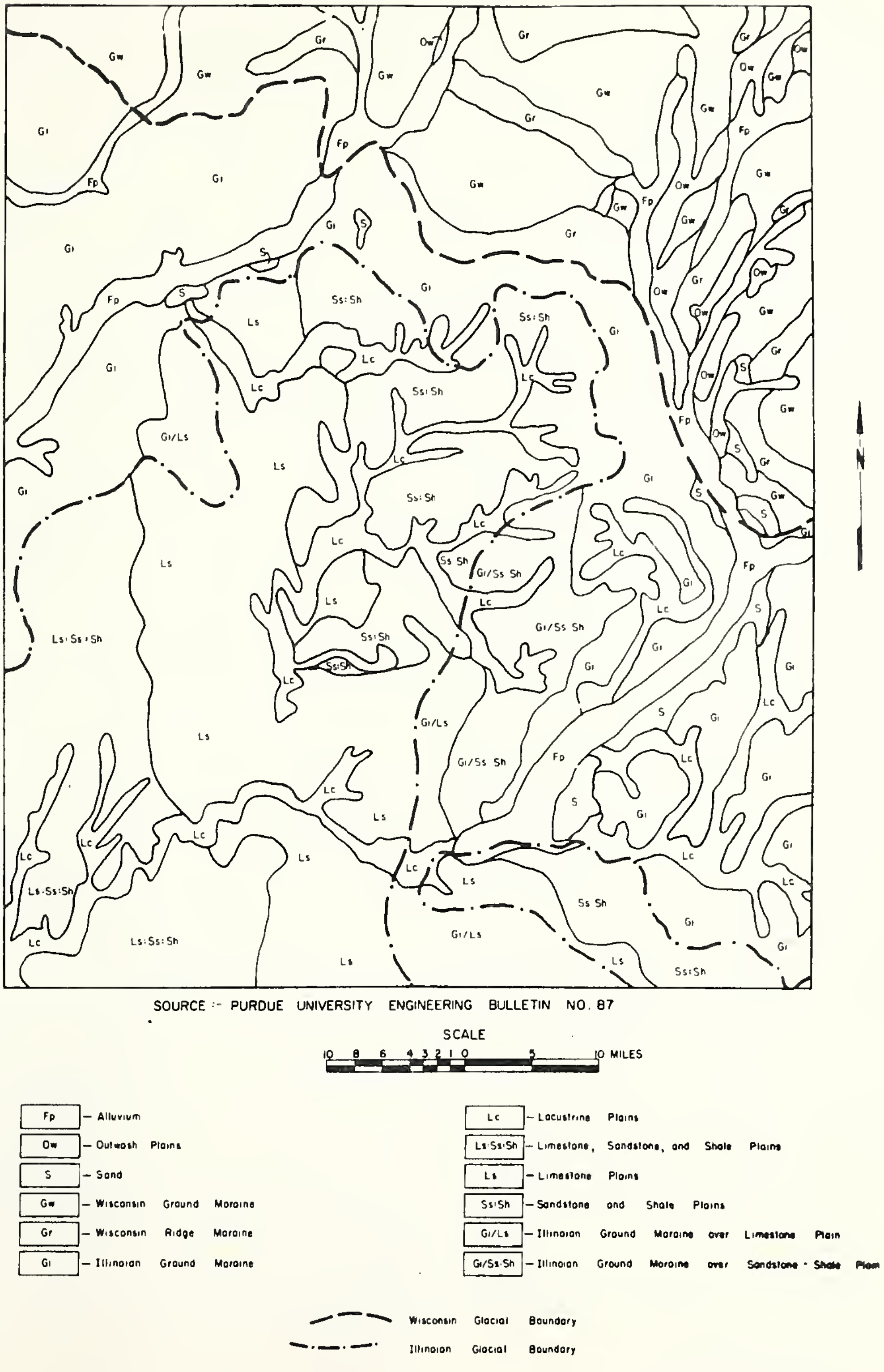
* Formerly the Commodity Stabilization Service, United States Department of Agriculture.



SOURCE :- PURDUE UNIVERSITY ENGINEERING BULLETIN NO. 87

Gw
Gr
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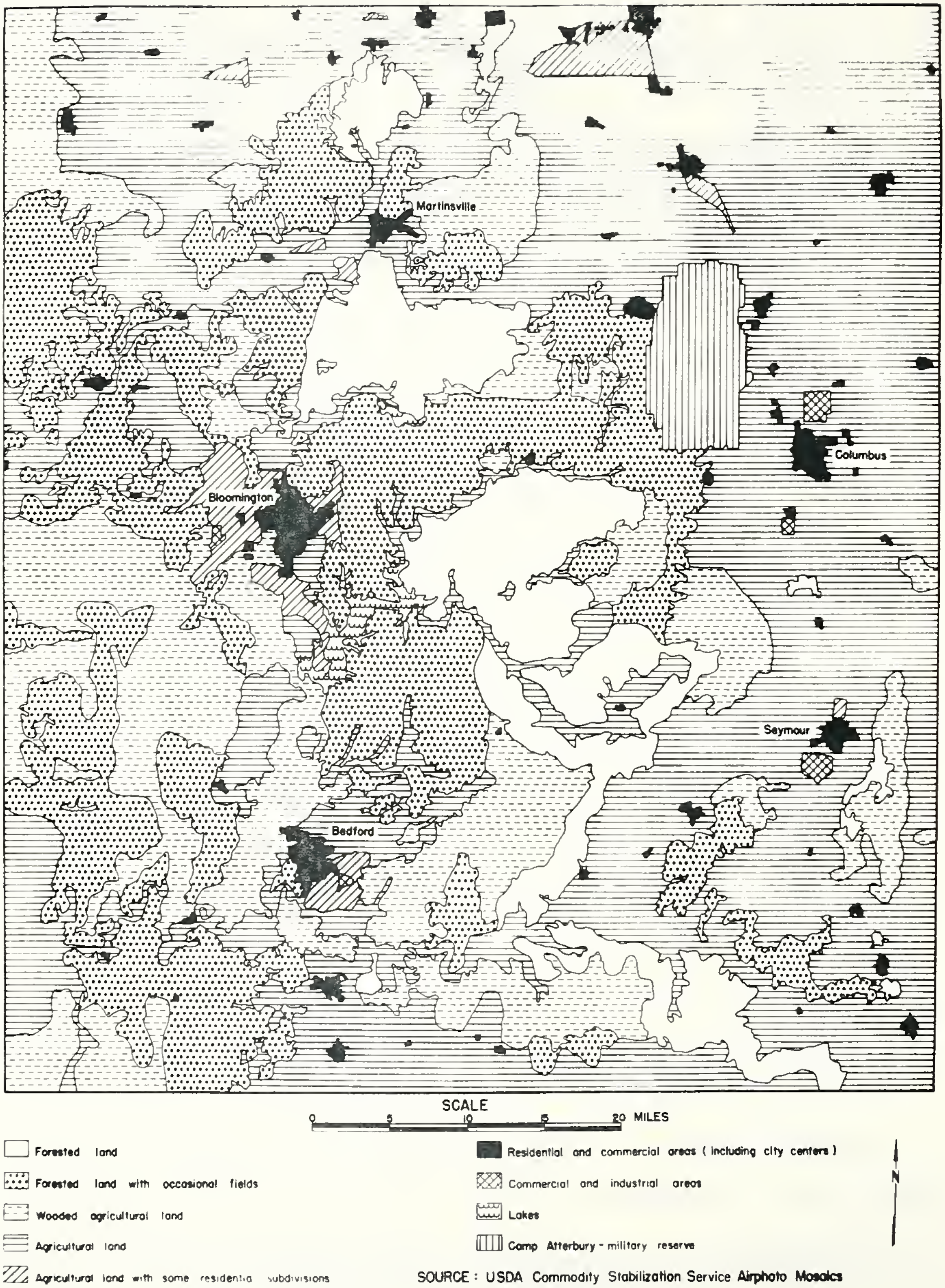
SCALE
10 8 6 4 3 2 1 0 5 10 MILES
Fp — Alluvium
Ow — Outwash Plains
S — Sand
Gw — Wisconsin Ground Moraine
Gr — Wisconsin Ridge Moraine
Gi — Illinoian Ground Moraine
Lc — Lacustrine Plains
Ls:Ss:Sh — Limestone, Sandstone, and Shale Plains
Ls — Limestone Plains
Ss:Sh — Sandstone and Shale Plains
Gi/Ls — Illinoian Ground Moraine over Limestone Plain
Gi/Ss:Sh — Illinoian Ground Moraine over Sandstone - Shale Plain
Wisconsin Glacial Boundary
Illinoian Glacial Boundary

FIGURE 26. ENGINEERING SOILS MAP OF SOUTHERN TEST AREA.


Martinsville
Bloomington
Columbus
Seymour
Bedford
SCALE
0 5 10 15 20 MILES
Forested land
Forested land with occasional fields
Wooded agricultural land
Agricultural land
Agricultural land with some residential subdivisions
Residential and commercial areas (including city centers)
Commercial and industrial areas
Lakes
Camp Atterbury - military reserve
N

SOURCE: USDA Commodity Stabilization Service Airphoto Mosaics

FIGURE 27. LAND USE MAP OF SOUTHERN TEST AREA

Plain, Tipton Till Plain, and Scottsburg Lowland regions. Farming is restricted to narrow upland and bottomland zones in the other areas. Industrial, commercial and residential activities are located in the two population corridors near the larger towns.

Description of Northern Test Area

The northern test area lies in the north-central part of Tippecanoe County, Indiana. It covers slightly less than one half the county, having an east-west width of 13.3 miles and a north-south length of 17.8 miles.

It lies within the Tipton Till Plains physiographic region of Indiana, as defined by Malott [62, 99]. Figure 28 shows the important topographic characteristics of the area. The surface is a gently undulating plain sloping toward the entrenched Wabash River valley from both the northwest and southeast. Remnants of poorly defined morainic ridges are scattered throughout the area, but are especially prevalent along the southern edge and in the northwestern corner. These areas form an undulating to rolling surface having a few tens of feet of local relief. Elsewhere the upland surface is almost level. A few conical hills are found near Dayton. Occasional depressions filled with muck and peat are found; the largest lies just west of West Lafayette.

Drainage throughout the area flows into the Wabash River. Most important tributaries are Wea and Wildcat Creeks on the south, and the Tippecanoe River, Burnett's Creek and Indian Creek on the north. A low depression of uncertain origin connects the headwaters of Indian and Burnett's Creeks.

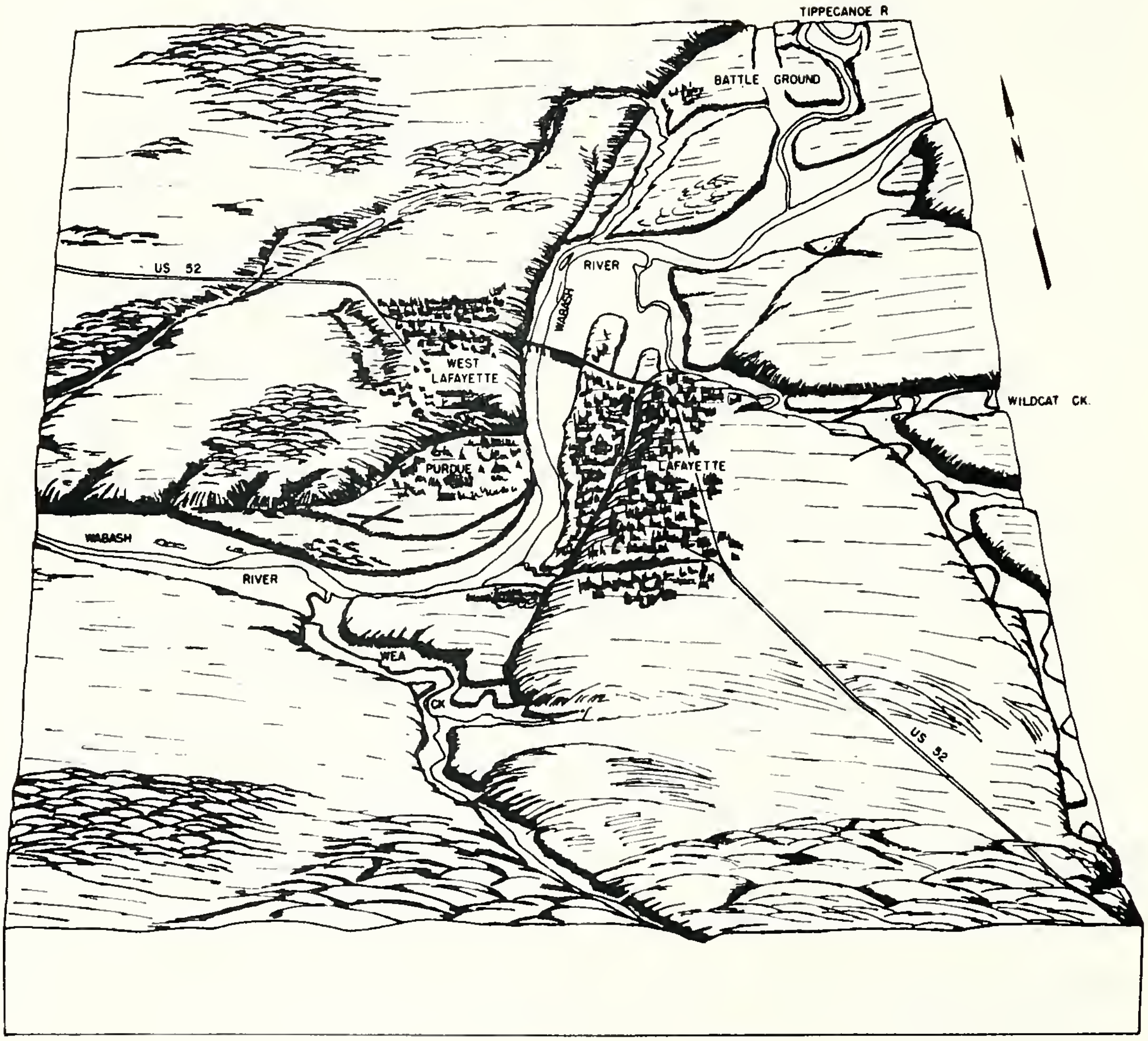


FIGURE 28. PHYSIOGRAPHIC DIAGRAM OF THE NORTHERN TEST AREA.

The Wabash River valley is the most striking feature. It is an entrenched valley that has been filled by glacial debris and re-excavated. The valley has wide terraces and a comparatively narrow flood plain. Two terrace levels are prominent. Where they are absent the valley walls are very steep and rugged, especially the west valley wall north of West Lafayette.

The entire area is covered with Wisconsin glacial drift. Bedrock, mostly shale, outcrops along the Wabash River near Americus in the northeastern part of the test area, and along Indian Creek south of Klondike. Figure 29 shows that part of the Tippecanoe County Engineering Soils Map prepared by Yeh [133] which covers the northern test area. The map shows the large terraces and outwash plains underlain by coarse granular materials which extend along the Wabash River and across the area south of Lafayette. Lesser amounts of outwash are found along the valleys of Wildcat Creek in the eastern part of the area and Indian Creek in the western part of the area. Figure 30 shows those areas underlain by granular outwash and alluvium. The remaining upland soils are mostly silty clays, except for local depressions filled with organic clays, muck, or peat. A thin layer of wind blown silt (loess) mantles many of the upland areas, especially near the Wabash Valley.

Figure 31 shows the present land use characteristics of this area. Much of the area is agricultural, except near Lafayette or West Lafayette. Scattered subdivisions are located east and south of Lafayette and west and northwest of West Lafayette. Figure 31 was prepared in part from data developed by Golenberg [31]. These data were applicable to only the metropolitan areas of Lafayette and West Lafayette and thus they were

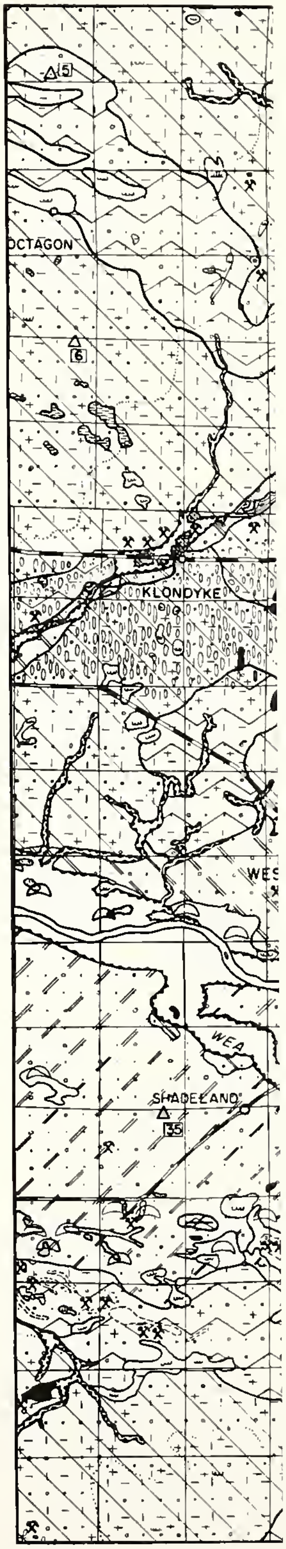
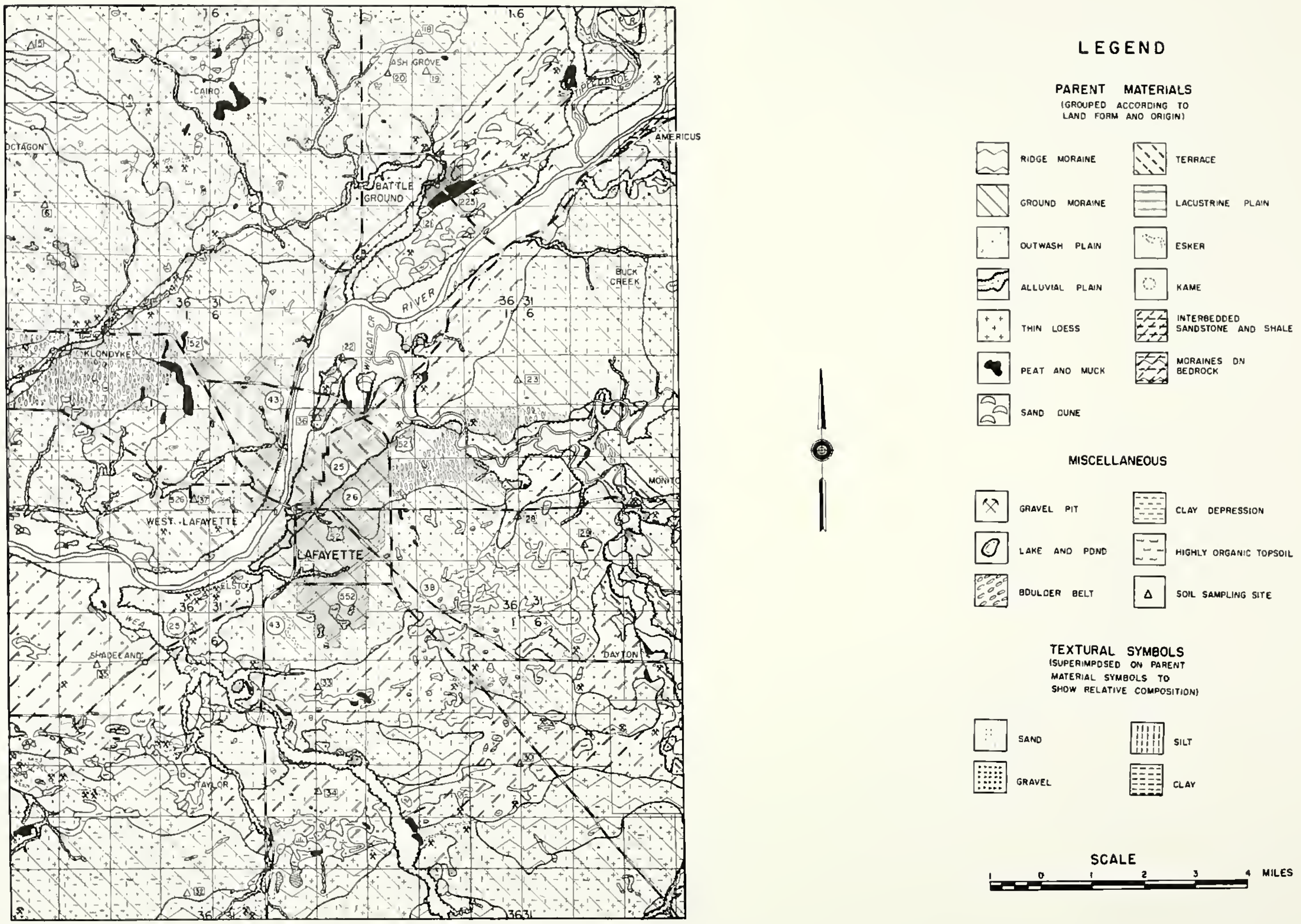
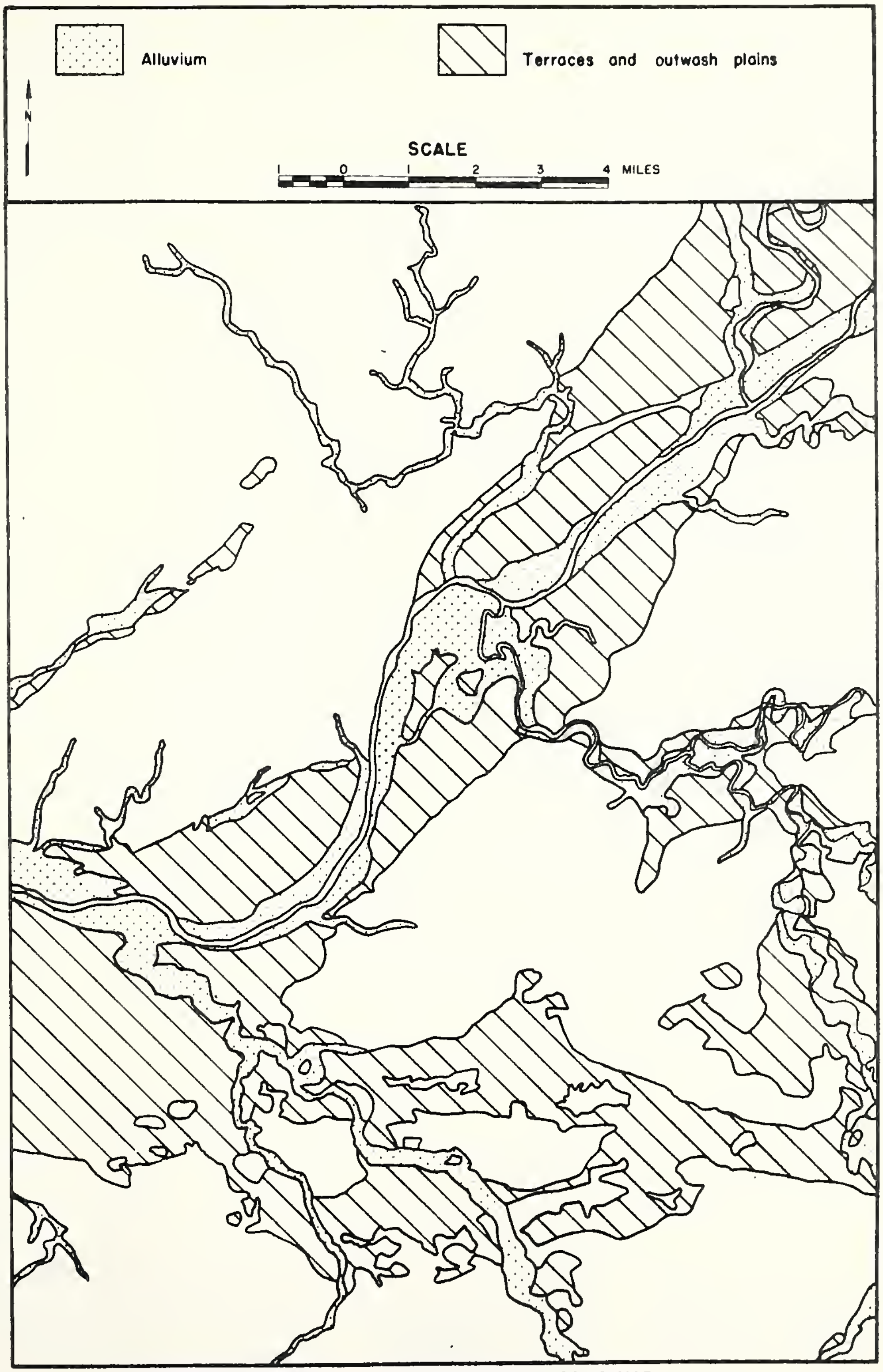


FIGURE 29.



SOURCE :- TIPPECANOE COUNTY ENGINEERING SOILS MAP

FIGURE 29. ENGINEERING SOILS MAP OF NORTHERN TEST AREA.



SOURCE:- TIPPECANOE COUNTY ENGINEERING SOILS MAP

FIGURE 30. LOCATION OF GRANULAR SOILS IN THE NORTHERN TEST AREA.

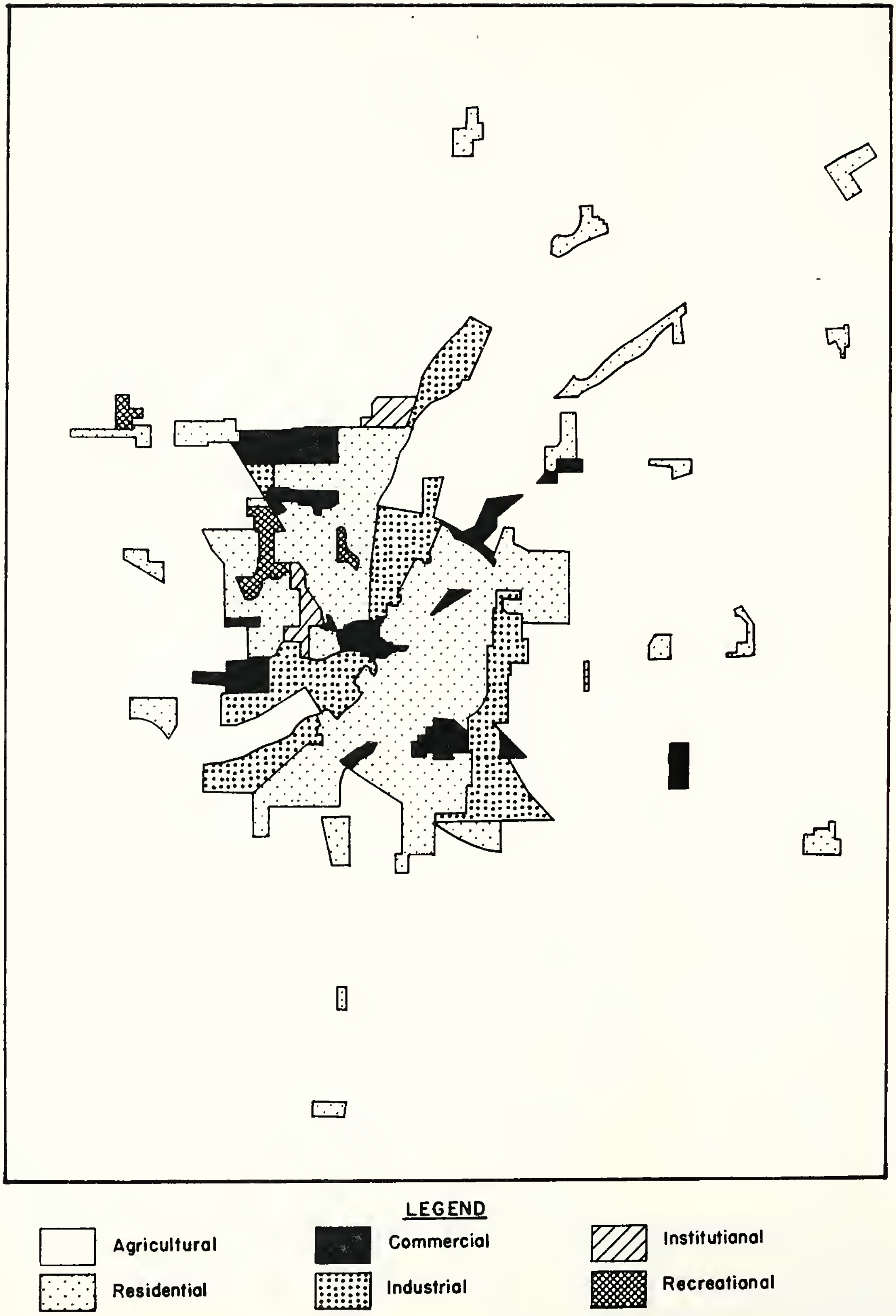


FIGURE 31. LAND USE MAP OF NORTHERN TEST AREA.

supplemented by other information. The land uses of the surrounding areas were mapped by studying aerial photographs taken in 1963 at a scale of 1:20,000. Golenberg defined 109 origin-destination zones each having a uniform land use, within the greater Lafayette area. The air-photo study of the surrounding areas added 104 zones bring the total number of zones within this study area to 213. Figure 32 shows the locations of all zones.

Data Collection Procedures

Selection of Data Sources

A suitable source of information for each of the four route independent factors had to be selected for one or more of the two test areas. A source of information for a factor is termed a "measure". Frequently more than one measure of a factor was utilized, in order to determine what types of data were most suitable. Measures for any particular factor varied somewhat from area to area due to scale differences and reflected changes in level of analysis within the highway planning hierarchy.

Table 4 shows the measures investigated for each route independent factor for each test area. In general the measures do not supply information on their factors which can be used directly by the GCARS System. As shown in Table 4 and Figure 21 (see page 94) these measures are progressively converted to "values," then to "utilities," before any generation of alternatives is possible. Description of these procedures is given later in this chapter under the heading "Data Analysis Procedures."

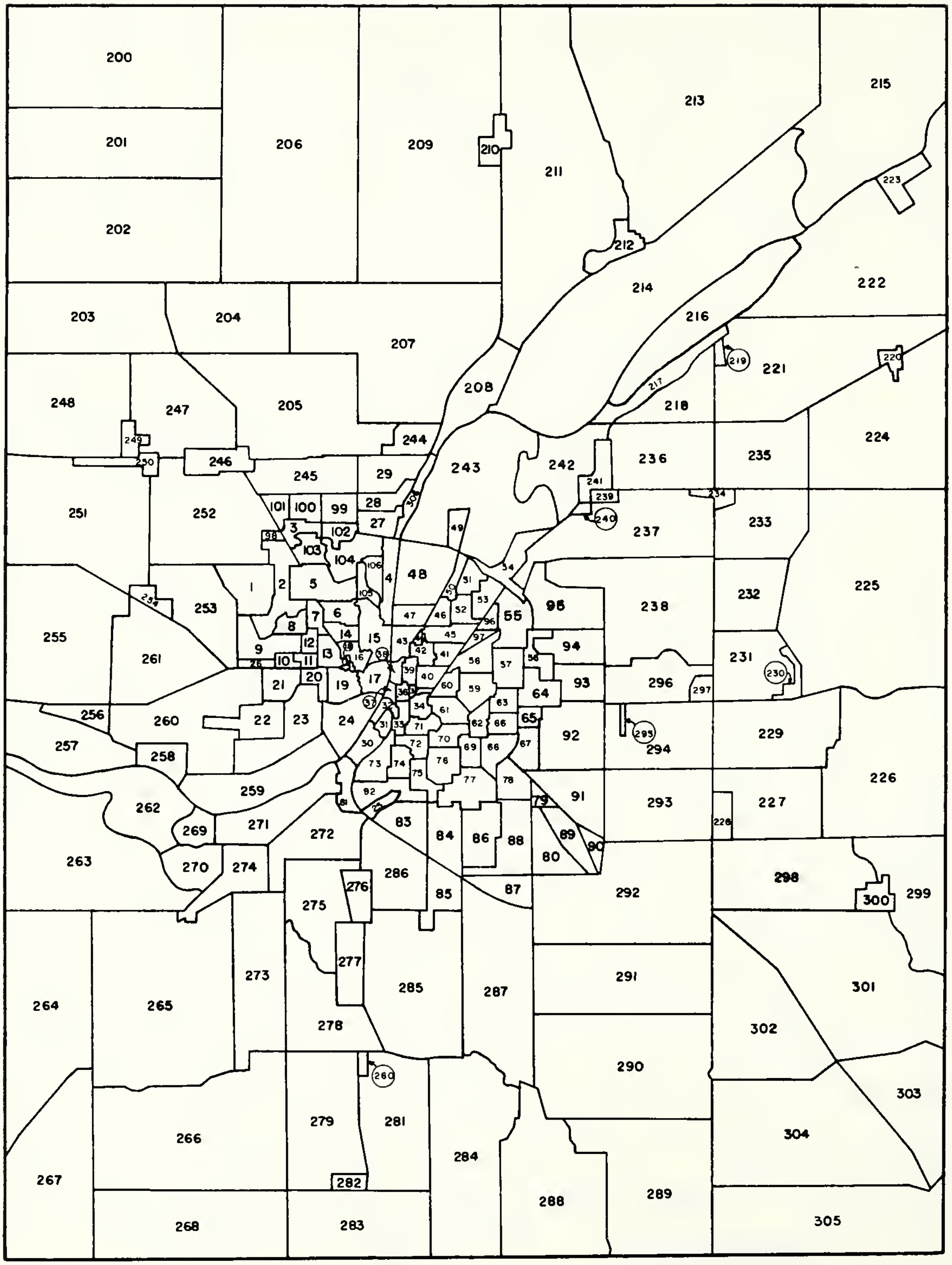


FIGURE 32. ORIGIN-DESTINATION ZONES IN THE NORTHERN TEST AREA.

TABLE 4

THE HIGHWAY LOCATION FACTORS STUDIED

Northern Test Area				
Factor	Earthwork Costs	Pavement Construction Cost	Right of Way Acquisition Cost	Service Benefits
Measure	1:24,000 Scale topographic maps	Tippecanoe County Engineering Soils Map	Land use categories for origin-destination zones	(a) Census data from 1960 National Census by census tracts. (b) Tippecanoe County Highway Maps
Measure transformed to Value by	Residuals to fifth degree trend surface fitted to topographic data.	Rating scale based on soil ratings determined by Ulbricht.	Rating scale devised by author.	(a) Population totals determined for each zone (b) Population densities for each zone (c) Trip ends for each zone (d) Road intersection rating scale devised by author
Southern Test Area				
Factor	Earthwork Cost	Pavement Construction Cost	Right of Way Acquision Cost	Service Benefits
Measure	(a) 1:250,000 scale topographic maps (b) 1:24,000 scale topographic maps	State of Indiana Engineering Soils Map.	Land use map prepared by interpretation of airphoto mosaics.	(a) Census data from 1960 National Census (b) 1:250,000 scale topographic maps
Measure transformed to Value by	Residuals to - (a) fifth degree trend surface fitted to elevations from 1:250,000 scale maps. (b) fifth degree trend surface fitted to elevations from 1:24,000 scale maps (c) fifth degree trend mosaic	Rating scale based on soil ratings determined by Ulbricht.	Rating scale devised by author.	(a) Populations of all incorporated towns and cities. (b) Population densities for approximately 20 square mile zones. (c) Road intersection rating scale devised by author.

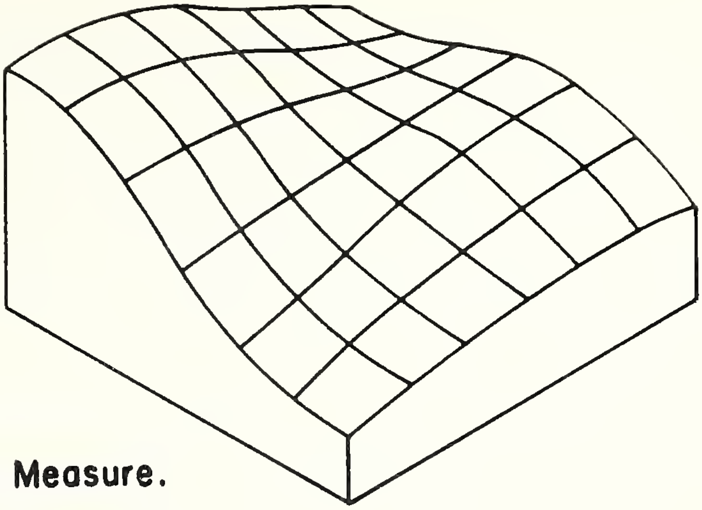
Classification of Measures

There are two types of measures; graphical measures (maps) and numerical measures. Map digitization, the reduction of graphical to numerical measures, is required before computer analysis is possible. Digitization is accomplished by "sampling" the map at a number of observation stations. The entire subsequent analysis depends on the quality of the data collected; thus the development of simple, logical, and reproducible sampling procedures for all measures is an important prerequisite to the successful application of the GCARS System.

Three kinds of measures can be distinguished. These are termed "continuous," "discontinuous," and "discrete." Any measure is composed of a large number of individual observations, the whole forming in statistical terms, a "population" or "universe" [22, 23]. Ideally a mathematical equation, perhaps of considerable complexity, can be fitted to each population. The original population, or the derived function, will take one of three forms, as shown in Figure 33.

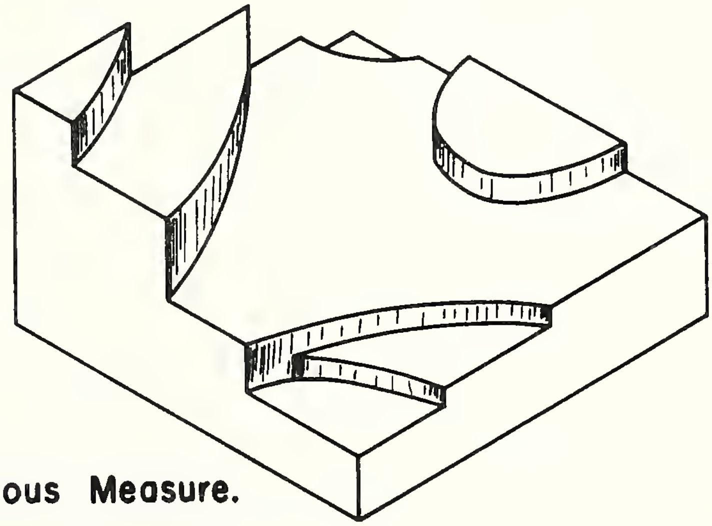
A continuous measure (Figure 33-A) has smoothly changing values so that a uniquely defined value is associated with every position. It is termed a continuous measure becuase the derived equation will be in mathematical terms a continuous function. The Earth's surface is an example of a continuous measure.

A discontinuous measure (Figure 33-B) can be visualized as a series of irregularly shaped stairsteps or plateaus. Each "step" has an elevation representing its value, but discontinuities exist between steps since no unique value can be assigned to a point lying on the step boundaries. Maps which show the distribution of similar entities, such as



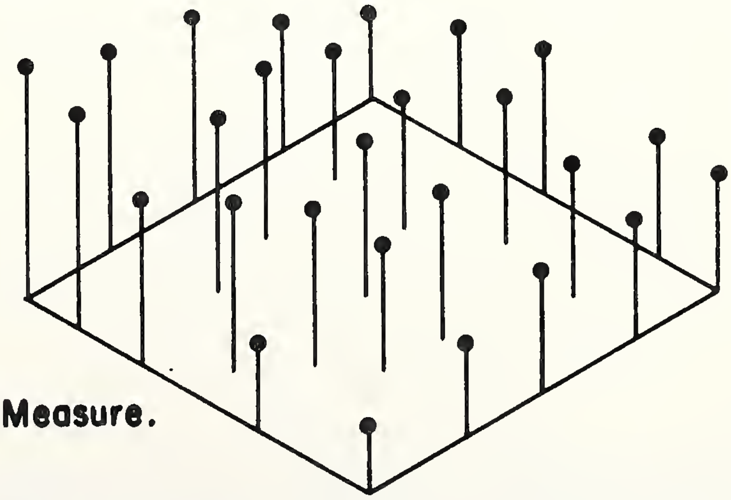
A)

Continuous Measure.



B)

Discontinuous Measure.



C)

Discrete Measure.

FIGURE 33. THE THREE TYPES OF MEASURES.

soil and geology maps, are examples of discontinuous measures.

The third kind of measure is shown in Figure 33-C. A discrete measure is one which can be defined only at certain places. For example, measurement of road intersection characteristics can only be undertaken at road intersections which are located at certain discrete positions in space.

The discontinuous measures can be further subdivided into "homogenous discontinuous measures" and "heterogeneous discontinuous measures." Figure 34 shows the difference. Each homogenous unit of a discontinuous measure has a single associated value represented by its level surface. In contrast, each unit of a heterogeneous discontinuous measure has an associated range of values distributed according to some probability function. This may be represented by a wavy or sloping surface.

Substitution of Measures

It is possible to approximate continuous measures by discontinuous ones. For instance, classification of continuous measures into standard units transforms them into discontinuous measures. Such an approximation often results in a loss of information because knowledge of within unit variation is suppressed.

A heterogeneous discontinuous measure can be approximated by a homogenous discontinuous measure through the use of an appropriate statistic to represent the probability density function. For instance the mean, median, or mode can be used to represent the average value, while the variance or standard deviation can be used to represent the inherent variability. The approximation of a heterogeneous discontinuous function by a homogeneous one also results in a loss of information.

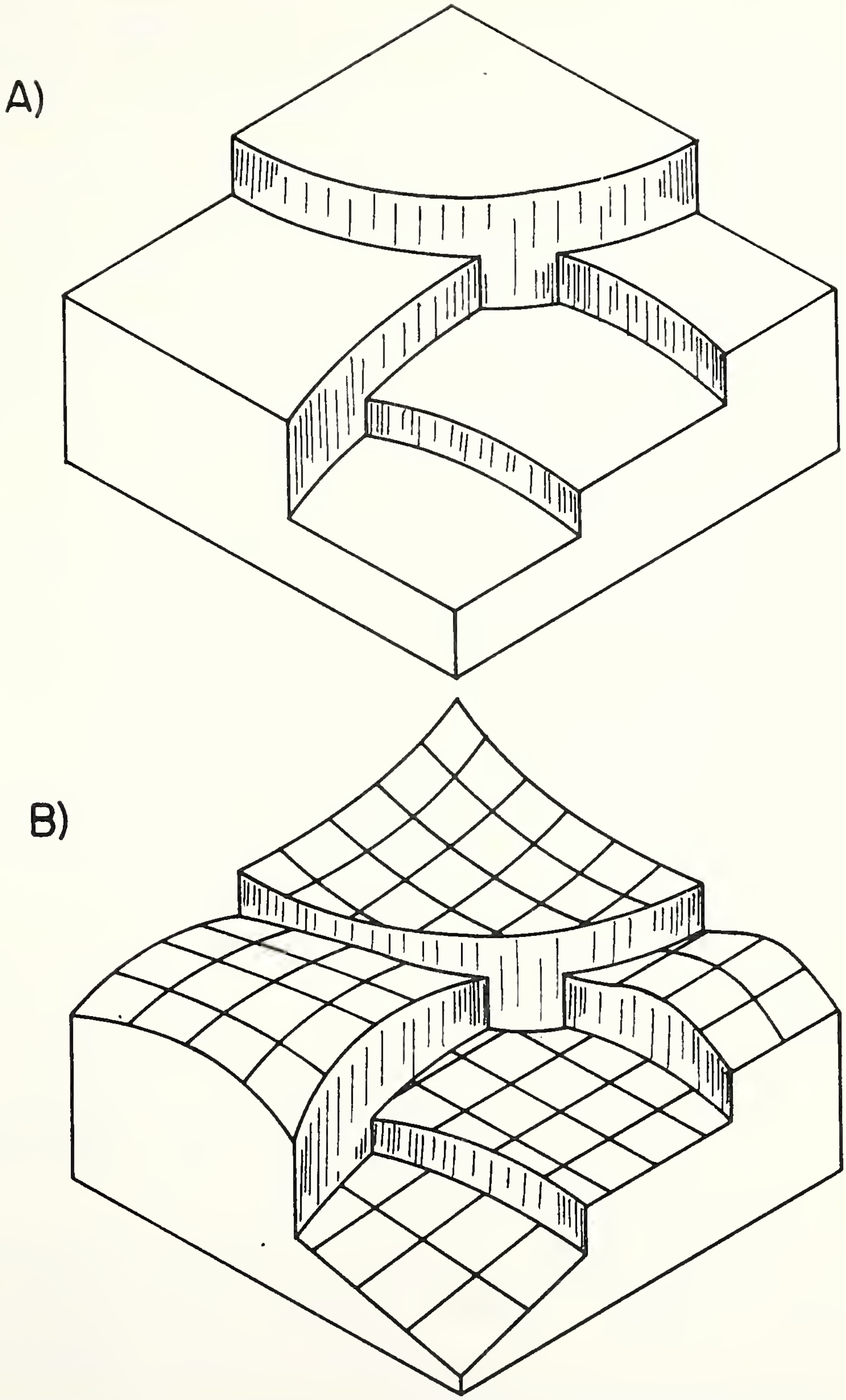


FIGURE 34. HOMOGENEOUS AND HETEROGENEOUS DISCONTINUOUS MEASURES.

These substitutions and their associated information losses are well demonstrated during the preparation of geologic and pedalogic maps. McIntyre [78] has attempted to study and define these various "levels of error" in connection with certain geochemical studies. Generally however soil scientists have been more cognizant of this problem than geologists. The Seventh Approximation, the most recent soil classification system proposed by the U.S. Department of Agriculture [119], describes the current concepts. The fundamental soil unit is the "pedon" which is defined as

> "a three dimensional body of soil with lateral dimensions large enough to permit the study of horizon shapes and relations. Its area ranges from one to ten square meters..."

A "soil" or "soil individual" is defined as follows:-

> "A soil consists of one or many contiguous pedons, bounded on all sides by "not-soil" or by pedons of unlike character."

The individual pedons, alone or associated as soils, form a continuous measure. The boundaries between soils "are often gradational and difficult to locate precisely in the field" [119].

The construction of a soil map requires classification and grouping of soil individuals into "soil series." The Seventh Approximation states:-

> "The areas identified by soil maps as to series are at best rough representations of the soil individuals.... As soil maps are usually made, the use of a series name merely indicates that the major part (85 percent or more) of the area belongs to that series."

Thus the soil map becomes a discontinuous measure, an approximation to the field conditions. Furthermore, because it suppresses all information about the actual field variations occurring within any particular area mapped as a soil series, it can be utilized only as a homogeneous discontinuous measure. Actual field sampling programs within mapped units can be designed to reflect their heterogeneity, however [119].

Design of Sampling Procedures

Different sampling procedures are utilized for each kind of measure. Discrete measures are the simplest to sample. Sample locations are limited to a finite number of clearly defined positions. If this number is not unduly large it is possible to sample the entire population. This was the case, for instance, when the road intersection characteristics were measured in the northern test area. The total number of road intersections shown on the county highway map is 402; thus all were sampled.

If the total number of observations is too large, limiting criteria can be applied. For instance, only alternate road intersections can be measured, thus halving the number of observations. Alternatively, all road intersections can be numbered and those ending in certain digits can be omitted, thus developing a random sample. Finally only those intersections belonging to certain categories can be studied developing a biased sample which ignores extraneous conditions. When sampling the road intersections in the southern test area, for example, only those intersections involving, at least, one "hard-surface, medium duty, two-lane road" were utilized. The criteria eliminated all gravel road-gravel road intersections and reduced the number of sampled intersections to 1054. The resulting biased sample measured the distribution of major and secondary transportation routes only and ignored purely local distribution systems. This was believed acceptable at the Band and Corridor levels of the highway planning hierarchy.

Sampling procedures for discontinuous measures are only slightly more complex. Sufficient sample points are required to define the boundaries of the various map-units, plus a few extra points to "fill-in" the interior portions of the larger units, as shown in Figure 35.

In designing such a sampling procedure the operator should consider the amount of detail, or resolution, required in the finished product. The resolution should be stated as some linear distance at the map scale. Features smaller than this resolution value can properly be ignored. Thus the total number of points required is a function of the number of discrete map units shown on the map and the required resolution.

The above procedure is applicable to homogeneous discontinuous measures and requires modification if applied to heterogeneous discontinuous measures. Such measures are heterogeneous because each map unit has an associated known variability within it. Thus each unit has a different difficulty of measurement and in order to measure each unit with the same reliability, the sampling density (number of samples per unit area) for each unit should be adjusted to reflect its inherent variability. In this way roughly uniform sampling reliability is obtained over an entire map. A suitable measure of the inherent variability within each unit must be developed.

As has been already discussed, continuous measures are rarely shown on maps. Topographic maps portray the Earth's surface which is a continuous measure (in the absence of vertical cliffs). However this continuous surface is not uniformly easy to sample. Closely adjacent points can include a great variety of relationships which collectively form "topography." Topography is classifiable into any number of categories which are frequently given names such as "smooth," "rolling," "hilly," "crested," etc. Topographic maps show these differences by contour line

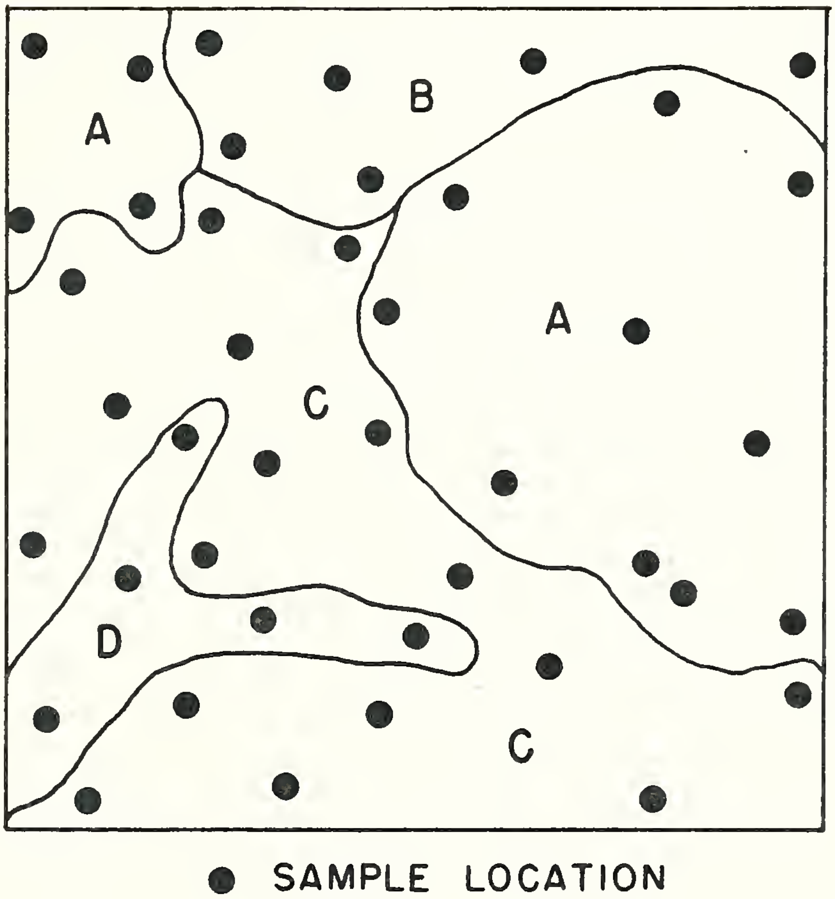


FIGURE 35. SAMPLING PROCEDURES FOR DISCONTINUOUS MEASURES

patterns of different types. It is possible to subdivide topographic maps into areas containing different kinds of topography. This subdivision converts a continuous measure into a heterogeneous discontinuous one, since each type of topography has an associated difficulty of sampling.

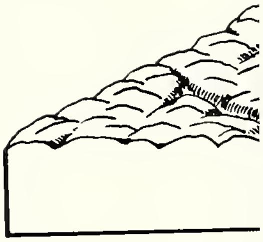
As discussed in Chapter III, vector analysis procedures were developed by Hobson [41] to measure terrain roughness. These procedures were carefully studied and extended as part of this project, and a terrain variability factor was defined as follows:-

$$\text{terrain variability factor} = \frac{\text{range in elevation}}{\log\,(\text{roughness})}$$

Values of this factor are large in "rough" areas and small in "smooth" areas. Details of these experiments are described by Turner and Miles [115] and are summarized in Chapter III.

The terrain variability factor is used in designing a sampling procedure for a topographic map. Figure 36-A shows a hypothetical map area. The researcher can subdivide this topographic map into six subareas, each belonging to one of three categories. These are shown in Figure 36-B. The topographic map is now considered a heterogeneous discontinuous measure.

The fraction of the total map area belonging to each subarea can be estimated or it can be measured by a planimeter. The terrain variability factor for each subarea can be derived from data obtained by measurement according to specified procedures and computed by program VECTOR [41, 115]. Examination of Table 2(see page 54) shows that each category of terrain has an associated range of terrain variability factors. Thus with



A. BLOCK DIAGRA

B. MAP SUBDIV
SAMPLING.

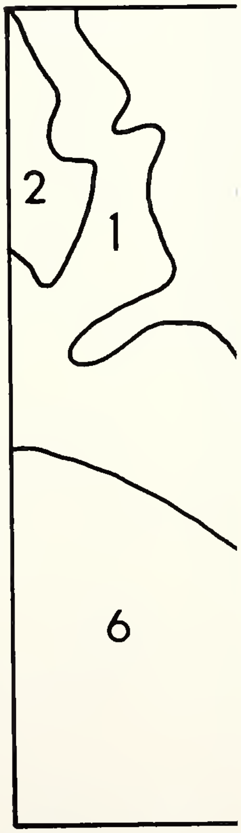


FIGURE 36. S

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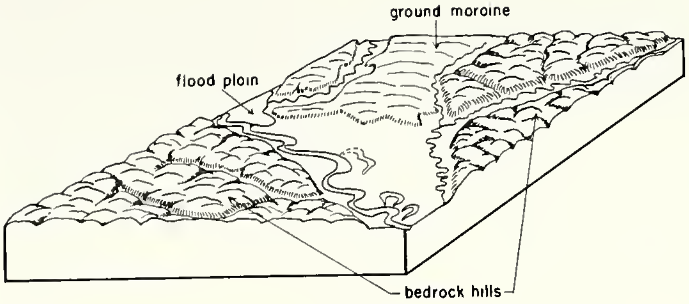
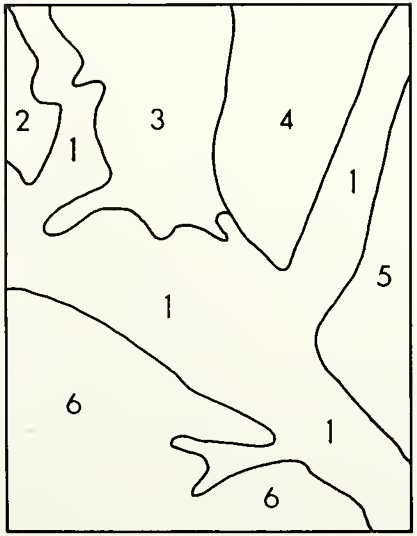


A. BLOCK DIAGRAM OF MAP AREA

B. MAP SUBDIVIDED FOR STRATIFIED SAMPLING.



C. SAMPLING DISTRIBUTION TABLE

SUBAREA	TERRAIN TYPE	ESTIMATED VARIABILITY v_i	FRACTIONAL AREA a_i	PRODUCT $a_i \cdot v_i$	SUBAREA SAMPLES n_i
1	FLOODPLAIN	5.0	0.36	1.80	22
2	GROUND MORAINE	15.0	0.04	0.60	9
3	GROUND MORAINE	15.0	0.13	1.95	23
4	HILLS	80.0	0.13	10.40	123
5	HILLS	80.0	0.10	8.00	95
6	HILLS	80.0	0.24	19.20	228
TOTALS			1.00	41.95	500

FIGURE 36. SAMPLING PROCEDURES FOR TOPOGRAPHIC MAPS.

experience an operator can estimate a terrain variability factor which is quite accurate. These values are entered in the appropriate columns of a sampling distribution table (Figure 36-C).

If the variability factor and the percent area belonging to each subarea on a map sheet, such as Figure 36-B, are known and the total number of samples to be distributed on the map is decided on, the following equation will distribute the points among the various subareas:-

$$n_i = \frac{v_i a_i}{\sum v_i a_i} \cdot N$$

where i is the subarea number, v_i is the variability of the ith subarea, a_i is the percent area of the ith subarea, and N is the total number of samples on the map. Such a distribution of sample points among the various subareas, will result in approximately equal sampling reliability over an entire map area. These calculations are shown in Figure 36-C. The summation of the products of the individual terrain variability factors and the subarea areas is the measure of the overall map variability and is termed the weighted variability number.

One problem remains. What value should be assigned to N, the total number of samples on the map? A relationship exists between N and the weighted variability number. It was decided to determine this relationship. Accordingly, six map quadrangles lying within the southern test area and having weighted variability numbers ranging from 14 to 154 were selected for further study.

Each map was digitized with 900 points. Trend surfaces were fitted to each map and each data set was interpolated to form gridded values at

a one half inch spacing over the entire quadrangle. A random selection of 450 points was obtained from the original 900 points and the trend surface and interpolation analyses were repeated. Each map was also sampled with 150 points as part of the elevation measure collected to study the earthwork cost factor in the southern test area. These data were also analyzed by trend surfaces and interpolated to form gridded values. In this way, three different sample distributions for each of the six quadrangles were analyzed in an identical fashion to produce trend surface and interpolated "original value" contour maps and associated matrices.

Graphical and quantitative map comparison procedures were used to interpret the results. The comparisons were made among the maps of each quadrangle independently of the other quadrangles. Graphical comparisons showed the first, second, and third degree trend surfaces to be very similar for all quadrangles. Accordingly the quantitative map comparison procedures suggested by Tobler [112] were used only to compare the fourth and fifth degree trend surface and "original value" maps for each quadrangle.

The quantitative methods produce a series of correlation coefficients as measures of map similarity. Using these values each type of map (fourth degree trend, fifth degree trend, or "original values") was studied in turn to determine the degree of similarity between the map produced from 900 points and those produced from the smaller sampling distributions. If the map produced from 450 points is almost identical to the one prepared from 900 points, but the map based on 150 points is markedly different, then a sampling rate of between 150 and 450 points is the minimum acceptable rate.

In order to define these minimum rates, plots were prepared showing the correlation coefficients versus the weighted variability number and the number of points sampled. These three dimensional plots were used to locate values of the weighted variability number and the number of points for which the correlation coefficients were approximately 0.98 and 0.90. These extracted values were used to prepare the graphs shown in Figures 37 and 38. These graphs may be used to select a suitable total number of samples for any map whose weighted variability number is known. Minimum acceptable sampling rates are indicated by those values falling within the shaded area for any weighted variability number.

The upper boundary of the shaded area corresponds to a correlation coefficient of about 0.98, the lower boundary to a coefficient of 0.90. The heavy dotted line represents the median values. Sampling rates that plot far above the shaded areas are "oversampled," many more samples having been taken than is necessary. Points lying below the shaded zone indicate "undersampling". In order to obtain reasonably stable trend surface equation coefficients, the ratio of sample points to coefficients should be three or better [82]. Thus a fourth degree trend surface (15 coefficients) needs at least 45 sample points and a fifth degree surface (21 coefficients) at least 63 sample points, irregardless of the map variability. These values therefore set lower limits on these sample distributions.

Comparison of the three graphs shows that for any value of the weighted variability number, the fourth degree trend surface requires fewer sampling points than the fifth degree surface, which requires less

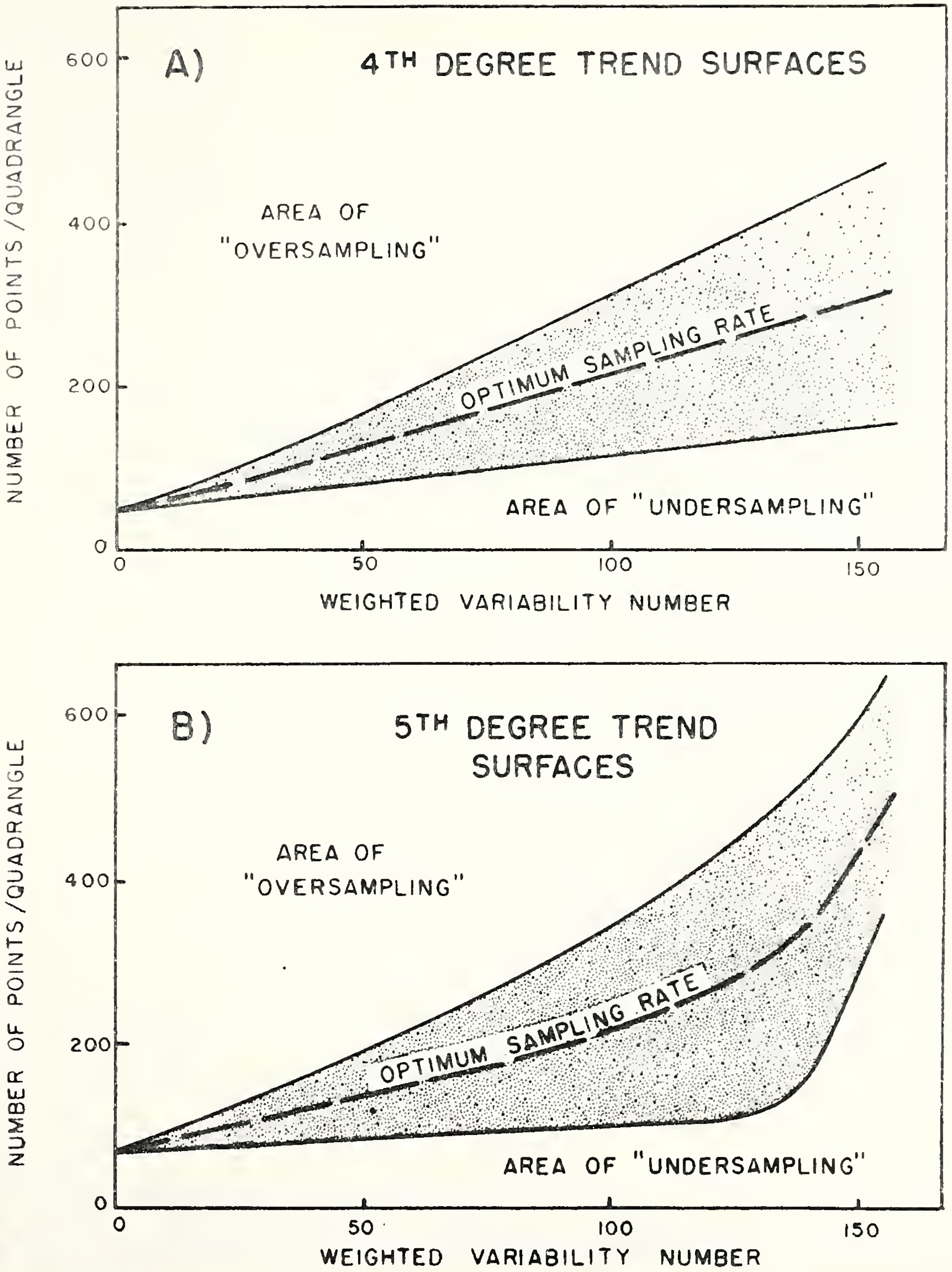


FIGURE 37. RELATIONSHIP BETWEEN MINIMUM SAMPLING RATES AND WEIGHTED VARIABILITY NUMBER FOR FOURTH AND FIFTH DEGREE TREND SURFACES.

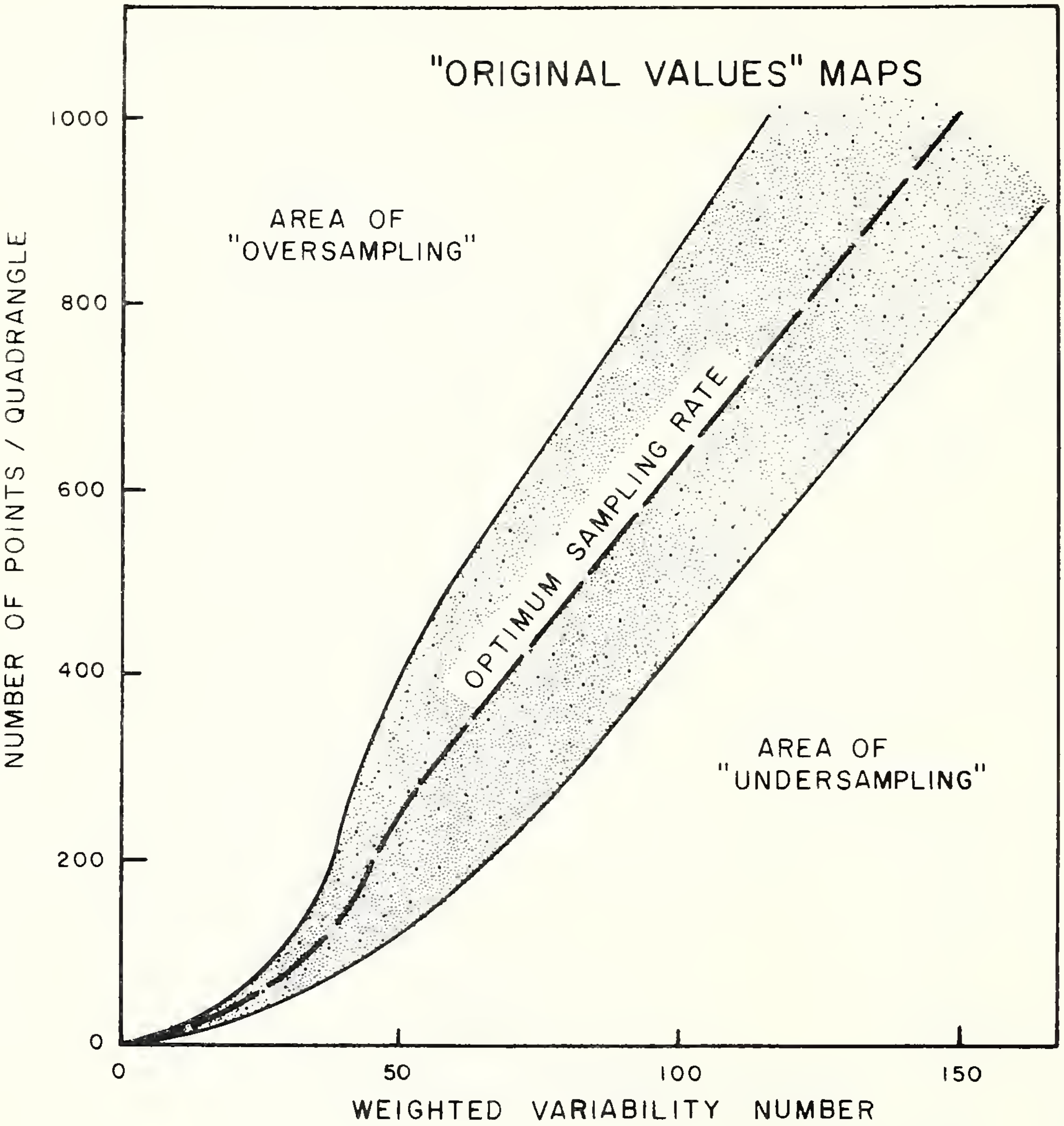


FIGURE 38. RELATIONSHIP BETWEEN MINIMUM SAMPLING RATES AND WEIGHTED VARIABILITY NUMBER FOR ORIGINAL VALUES MAPS.

sample points than the "original values" map. Furthermore, the interaction between the map variability and the number of samples required is much stronger for the "original values" maps than for the trend surfaces. This is shown by the almost 45 degree slope of the shaded zone in the last graph. All three graphs tend to show a wider dispersion of the shaded zone for higher weighted variability numbers. "Smooth" maps have limited variability by their very nature, while high values of the weighted variability number can be obtained on a variety of maps. The widening of the shaded zone reflects this condition.

Description of Sampling Equipment

Development of a prototype GCARS System required large volumes of data describing the various highway location factors in numerical form so that computer processing could be undertaken. Information on most factors is most conveniently available and is most readily understood when it is shown on maps. Thus some method of rapidly reducing maps to numerical measures was required.

Manual methods of sampling mapped data were used in early feasibility studies. These proved to be slow and cumbersome however. During development of the digital terrain model MIT engineers concluded that machine-assisted data collection procedures were eight to twelve times faster than manual methods and were more accurate [103]. Several commercially available "digital coordinatographs" are available. These machines automatically measure the X and Y coordinates of graphical data and, on command, record these values on paper tape, punched cards, or magnetic tape for computer processing. A Benson-Lehner Corporation* LARR-V (Large

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*now called Graphic Systems Division, Computer Industries, Inc., Van Nuys, California.

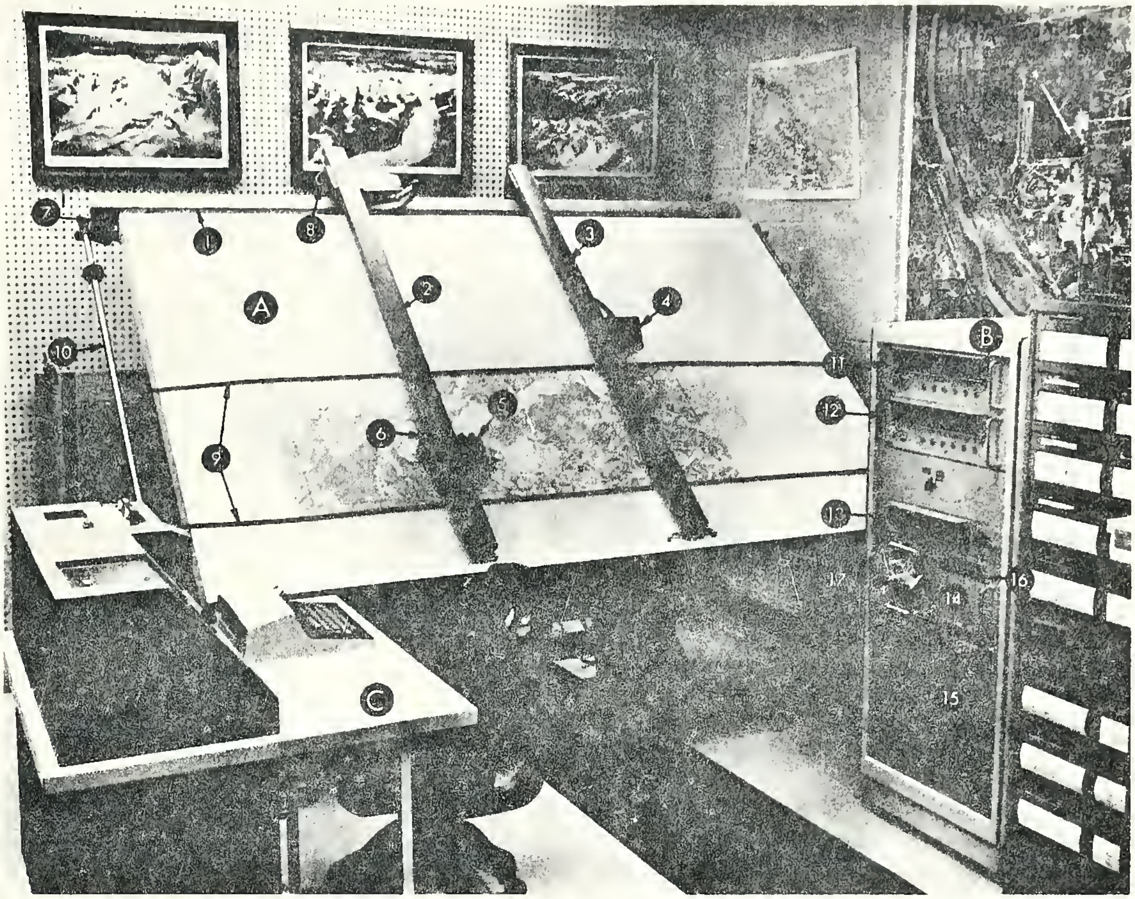
Area Record Reader - Vertical) was purchased along with an IBM model 029 card punch. Installation of the equipment took place on October 9, 1967. Except for occasional servicing, the system has operated satisfactorily since that time.

Figure 39 shows the equipment installed in the Airphoto Interpretation and Photogrammetry Laboratory. There are three basic units; (1) the reading table, (2) the Telecordex unit, and (3) the IBM model 029 cardpunch. Connection of the cardpunch into the system does not affect its capabilities in any way. Normal operation of the punch is possible except when it is receiving and punching information from the LARR-V unit.

The reading table consists of a standard 55 inch by 85 inch formica covered drafting table. The table can be tilted and used in any position from horizontal to vertical, and can be raised or lowered over a small range.

Three arms are mounted on the table (see Figure 39). The X-axis arm is rigidly mounted along the rear of the table. The Y-axis and keyboard arms are free to travel back and forth along it. A small carriage containing a readout switch and plastic cursor travels up and down the Y-axis arm. A twelve digit keypack is mounted on the keyboard arm, and is used to record "Z-axis" information, such as elevations from topographic maps.

The X and Y coordinates are measured by two "encoders." An encoder contains two plastic discs mounted on a shaft and two magnetic heads such as are found in tape recorders. The discs contain markings which can be "read" by these magnetic heads. A radio frequency signal is applied to the heads. When the encoder shaft is rotated the plastic discs move past



LEGEND

A THE READING TABLE
1 X-axis arm
2 Y-axis arm
3 keyboard arm
4 keypack
5 cursor carriage
6 readout button
7 X-axis encoder
8 Y-axis encoder
9 magnetic hold-down strips
10 roller for long charts

B TELECORDEX UNIT
11 X-axis telepack
12 Y-axis telepack
13 event counter
14 memory and control unit
15 power switches
16 constant data switches
17 patch panel

C IBM MODEL 029 CARD PUNCH

FIGURE 39. THE LARR-V DIGITAL COORDINATOGRAPH

the heads, the imprinted markings are read by the heads, and the signal is modified into a square wave containing clearly defined pulses. Differently shaped curves are obtained with clockwise and counter-clockwise rotations. Thus interpretation of the returning waves will indicate a direction and a distance by the shape and number of pulses encountered. The installed encoders measure 2000 counts per revolution and are attached so that one revolution corresponds to 5 inches of travel along either axis. Thus the basic resolution along either axis is 400 counts per inch (0.0025").

One encoder is mounted at the left end of the X-axis arm and is connected by a stainless steel cable loop to the Y-axis arm so that movement of the arm across the table causes rotation of the encoder shaft. The second encoder is mounted on top of the Y-axis arm and is connected so that movement of the cursor carriage up and down the Y-axis arm causes rotation of its shaft. The maximum usable reading area in a single setup is 60 inches in the X direction by 48 inches in the Y direction.

The Telecordex unit contains a number of sub-units (see Figure 39). On top there are two Telepack units which accumulate and store the count totals coming from the X and Y encoders. Continuous displays of these counts are given by a series of nixie tubes. Electrical transmission of the values to recording instruments is initiated when the operator depresses the readout button. An event counter unit is installed below the Telepack units. This unit records and displays a running count of the number of readouts taken by the operator.

The Telecordex also contains a memory and control unit. This unit contains (1) power switches for the system; (2) twelve constant data switches, each containing twelve positions (blank, minus, and ten digits, zero through nine) which can be used to enter fixed identification data as part of the data readout; (3) a patch panel; and (4) a memory buffer for the Telepack units.

The patch panel is used to select the options to be recorded and the sequence of these options. In conjunction with a standard format control (drum) card on the IBM 029 card punch, it allows the operator to select any of an extremely wide range of data formats. When the readout button is pressed by the operator, the instantaneous encoder count totals are stored in the memory unit and the options requested by the operator on the patch panel are sequentially fed to the card punch. At the termination of the readout sequence the event counter is advanced one selected increment and the buffer is opened to accept a new reading. Because their values have already been stored in the buffer, the encoder totals can be changed during the readout cycle; in other words, the operator can move the cursor to his next sampling position during the readout cycle.

If the operator wishes to enter Z-axis values via the keypack, this option must be requested at the appropriate place in the readout cycle. When this is reached the unit will pause until the values are entered on the keypack, then the readout cycle will be completed.

The unit is extremely flexible. At the beginning of a sequence the operator can insert initial values in the data switches, the event counter and the X and Y-axis Telepacks. Adjustments can be made to the Telepacks so that the origin can be anywhere on or off the drafting table and the positive direction of either axis can be modified so that sampling can be undertaken in any geometric quadrant. Any option can be requested many times within a readout cycle, and many readout cycles can be placed on a card.

Sampling Accuracy and Rates

The overall system accuracy, as described by the manufacturer, is ±0.010 inch from any point to any point within the 48 by 60 inch digitizing area. The maximum counting rate of the encoders is 50,000 counts per second, which at the currently available maximum counting density of 400 counts per inch, equals a movement of 125 inches per second along either axial direction. Speeds beyond this rate would cause "lost-counts" but these should not be encountered in practice.

The sampling rate is affected by a number of factors, chiefly the following:-

(1) the card feed transit time and punching speed of the IBM 029 card punch,
(2) the amount of data requested in a readout cycle,
(3) the type of data requested in a readout cycle,
(4) the type of source data being digitized,
(5) the skill of the operator
(6) the number of readout cycles placed on a card,
(7) the quality of the cards being punched.

Table 5 gives some typical sampling rates for some commonly used data combinations. The rates are based on experience gained during the project. In those cases where the data are all being supplied by the machine, it is important to place as much data as is convenient on a single card. Otherwise the sampling rate becomes dependent on the card release-feed cycle time of the card punch. Such situations are less

TABLE 5

DATA DIGITIZATION SPEEDS ON THE LARR-V CO-ORDINATOGRAPH

Type of Data	Sampling Rate[1]
1) X and Y co-ordinates from cross-sections or graphs.	400-475 points/hour[2]
a) multiple data sets on one card	440-475 points/hour
b) single data set on a card	400-450 points/hour
2) X, Y, and Z co-ordinates, when Z co-ordinate can be set on fixed data switches and punched automatically.	350-400 points/hour[3]
3) X, Y, and Z co-ordinates, when a Z co-ordinate of no more than three digits is entered by the operator from the Keypack.	250-350 points/hour[4]
a) topographic data from 1:24,000 scale maps	300-350 points/hour
b) topographic data from 1:250,000 scale maps	250-300 points/hour
4) X, Y, and Z co-ordinates, when a Z co-ordinate of more than three digits must be entered from the Keypack.	less than 200 points/hour

(1) Rates based on experience during this project and are representative of rates achieved under normal conditions with an experienced operator.

(2) Rate depends on quality and characteristics of the graph.

(3) Engineering soils maps, land use maps, and similar maps are examples of this type of data.

(4) Rate depends on complexity of map, contour interval, and frequency of contour interval identification. The latter largely accounts for the slower rates for 1:250,000 scale maps.

likely to occur when the manual keyboard is required.

When topographic elevations are being measured the operator often has to count the contour intervals from a known elevation before punching the value on the keyboard. The quality of the map being digitized and the skill of the operator will greatly affect the sampling rates under these circumstances. It was found for instance that the small scale 1:250,000 topographic maps were more difficult to sample than the 1:24,000 scale maps because the actual contour values are shown less frequently on the small scale maps. As a consequence the operator had to search for these values from time to time.

Of course, if the cards being used are warped or damaged in any way, card-feed problems will develop which will greatly slow down the sampling rate. It was for this reason that the equipment was placed as shown in Figure 39. While sitting at the reading table the operator was within easy access to all controls on both the card punch and the telecordex unit.

Data Analysis Procedures

Measures, Values, and Utilities

A "measure" has already been defined as "a suitable source of information for a factor." For example, an engineering soils map contains basic information needed to evaluate the pavement construction cost factor, and thus is a measure for the factor. It is but one form of a soils map, however, and other maps are also measures of the same factor.

Measures do not supply all the information on their factors that is needed by the GCARS System. Often measures have to be transformed so as to reflect either the costs which will be incurred or the benefits which will accrue in terms of particular factors. Such transformed measures are termed "values." A "value" may be defined as "a function of a factor reflecting either costs or benefits according to some quantitative or semi-quantitative scale." Values may be defined without direct reference to either dollar costs or dollar benefits. Values are a spatial phenomenon; thus it is possible to discuss and graphically portray "value surfaces."

A value surface may be either a cost surface or a benefit surface. Each value surface has a unique vertical scale representing the particular value function or rating system used to derive it. The GCARS System generates alternatives through repeated application of minimum path analysis procedures. What is desired however is to maximize benefits and to minimize costs. Thus benefits should be considered as the inverse of costs. Obviously values are not always suitable for minimum path analysis and in the general case a further transformation is required.

Transformed values are termed "utilities." A utility is defined as:- "a function of a factor reflecting either costs or benefits in a form suitable for minimum path analysis and having a standardized range of values so that addition with other utilities is possible in known ratios." Utilities are also spatial phenomena, and thus form utility surfaces.

Values representing costs can be transformed to utilities by merely standardizing their range of values. Values representing benefits must be inverted as well as standardized, so that areas of high benefit values on the value surfaces become low areas on the utility surfaces. Then minimum path analysis of the utilities will result in maximization of the benefits. Figure 21 (see page 94) and Table 4 (see page 115) show the interrelationships between factors, measures, and utilities.

In the prototype GCARS System, measures, values, and utilities are stored in the computer as matrices. The transformations just described therefore involve simple matrix algebra.

Development of Utility Networks

As described in Chapter III (page 80) minimum path analysis is performed only on a particular type of graph called a network. In a network each link connecting two nodes has up to two measures of desirability of travel, since travel may be in either direction. These measures are termed the capacity, resistance or value of the links and can be measured in any convenient units.

In the present situation, the utility matrices can be considered to form the nodes of a network. There are a large number of possible methods of joining the nodes to form a network. The simplest method perhaps, is the one chosen; all rows and columns in the matrix were joined to form a square network having a link to node ratio of almost four. The link capacities were computed as the average of the utilities of their two end nodes. The links were assumed to be undirected, having the same capacity for travel in either direction. On this basis a link table was constructed which described each link, in each direction, by origin node, destination node and its associated capacity. These networks are termed utility networks. The data are now in a form suitable for minimum path analysis.

Generation of Single Factor Alternatives

Before the minimum path analysis can begin, a suitable origin and destination must be selected and defined by their nearest nodes.

The prototype GCARS System utilizes the Road Research Laboratory (RRL) minimum path algorithm described in Chapter III (page 84). The algorithm was modified according to the procedures defined by Ayad [8] so that a series of alternative routes could be generated. After the network is analyzed for the first minimum path between the designated origin and destination, the central links of the path are reassigned arbitrarily very high values and removed from further consideration. The revised network is reanalyzed to find a new minimum path which becomes the second choice and the process is repeated until a limiting criterion is met. In the prototype system generation of alternatives continued until either the latest path total equalled or exceeded twice the first choice path value, or until seven choices were evaluated.

Not all the links in the chosen paths are reassigned high values; those near the ends are allowed to retain their true values and thus may form part of several alternatives. This is necessary if the choices are not to become unduly constrained. Based on Ayad's studies, seven percent of the links in the path, three and one half percent at each end, were allowed to retain their original values. This value was rounded to the nearest link and was never allowed to drop below one link at each end.

As presently organized, the prototype GCARS System transforms the value matrices to utility matrices, constructs a network link table and performs the minimum path analysis in a single pass. Program NET performs the value to utility transformation and prepares the link table, then it calls on subroutine MPATH to perform the minimum path analysis. Details of these programs are to be documented and published at a later date [116, 117].

Generation of Multiple Factor Alternatives

Additional computation is necessary to generate alternatives for a combination of factors. First, a suitable combined utility matrix must be developed; second, a network must be derived from this matrix; third, minimum path analysis must be applied to this network.

In the prototype GCARS System these procedures are performed by program NETSUM and subroutine MPATH. Program NETSUM utilizes the value matrices for each factor being considered. These are evaluated sequentially. First they are transformed to utilities, then each is multiplied by a weighting factor specified by the engineer. The weighted utility values are added to form a new matrix containing the weighted values of the utilities for all factors being considered. A network is constructed as in the single factor case.

Subroutine MPATH performs the sequential minimum path analysis for this network in the same manner as for the single factor case. Any number of factors can be utilized in the analysis and the same factors can be combined in a variety of ways in a single job. On request, a copy of the combined matrix will be punched onto cards for later study or further analysis.

Evaluation of Generated Alternatives

Following the generation of the multiple factor alternatives the design engineer should study each to determine if any have marked advantages or disadvantages in terms of route-dependent factors. The total lengths of the various choices, as shown by the number of constituent links since each has a unit length, is an important and easily studied route-dependent factor. The shorter more direct routes having only slightly higher total costs may actually out-rank longer alternatives given a higher initial ranking.

Thus a careful evaluation and possible reordering of alternatives should be performed before the analysis is termed complete.

CHAPTER V

ANALYSIS OF SOUTHERN TEST AREA

Investigation of Route Independent Highway Location Factors

The pertinent characteristics of the southern test area are described in Chapter IV and are shown graphically in Figures 24, 25, 26, and 27.

Seven measures were selected to study the four route independent factors of earthwork cost, pavement construction cost, right of way acquisition cost and service benefits. The measures were displayed in graphical form, as maps. When possible, available maps were used as measures, but in other cases suitable maps had to be prepared. These were sampled to obtain numerical measures which were later converted to values and utilities. Some measures were converted to more than one type of utility or value. Table 4 (page 115) summarizes the measures, values, utilities and transformations studied.

Trend surface analysis was used to check the values for accuracy in evaluating the factors and for lack of bias. Afterwards, transformation of the values to utilities was undertaken, then single factor alternatives were generated. Generation of multiple factor alternatives followed. Finally the generated alternatives were evaluated and re-ordered as necessary to reflect route dependent factors.

The studies in the southern test area are of a regional nature, since the area is roughly 60 by 70 miles. Accordingly the analyses performed are considered to be representative of the Band or Corridor levels of the highway planning hierarchy. The analysis shows the utility of the GCARS System for such regional studies in moderately hilly country.

Derivation of Value Surfaces for the Earthwork Cost Factor

The general topographic conditions of the southern test area are shown in Figure 25 (page 101). In order to develop an estimate of the probable earthwork costs throughout the test area some procedure had to be devised for: 1) measuring the topographic elevations throughout the area, and 2) approximating highway grade lines for all possible routes.

The procedure used is similar to that proposed by Roberts [91] and shown graphically in Figure 7 (page 30). The elevations are measured from topographic maps. Trend surface analysis is used to obtain a series of smoothed surfaces of varying complexity. These trend surfaces are assumed to approximate all possible grade lines in the area while the residuals, measuring the lack of fit of these surfaces to the elevation data, represent the magnitudes of cut or fill required to build a highway having a grade-line following the trend surfaces. Because the trend surfaces are least squares regression surfaces, the volumes of cut and fill over the entire area should nearly balance, and therefore the volumes encountered along a random line across the area should approximately balance.

Obviously the grade-line defined by a trend surface is frequently much less steep than an actual highway grade line. In most cases however, the relative magnitudes of the cut or fill costs along a highway would remain approximately the same as those shown by the residuals, although the actual volumes might be less. The residuals are capable of defining those areas lying far above or far below the local mean elevation, a value which is likely to be approached by the road grade. Thus topographic residuals are a suitable value of the earthwork cost factor.

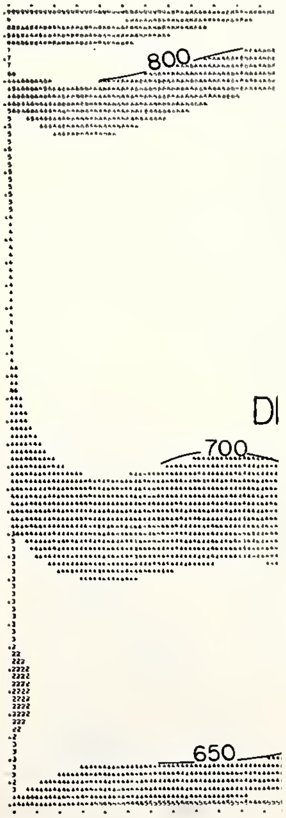
The elevation data can be obtained from a variety of maps, while the residuals can be obtained for any trend surface fitted to each set of data. In cases where the topography is too complex to be satisfactorily explained by a single trend surface, it is possible to fit trend surfaces to overlapping sections of the area. After such "piecewise" fitting of trend surfaces, a trend mosaic can be assembled from the various parts, much as a mosaic map is assembled from individual aerial photographs. Thus, there are several options available to the engineer desiring to evaluate the earthwork cost factor by topographic residual values. Three different ways of evaluating the earthwork cost factor were tried in the southern test area:-

1) overall trend surface analysis of the entire area using elevations obtained from 1:250,000 scale topographic maps,
2) overall trend surface analysis of the entire area using elevations obtained from 1:24,000 scale topographic maps,
3) mosaic trend surface analysis of four "quarter areas" using elevations obtained from 1:24,000 scale topographic maps.

Residuals to selected examples of each of these types of surfaces were obtained as values for the earthwork cost factor.

Elevation values at 900 locations were measured from the 1:250,000 scale topographic maps covering the test area. First through fifth degree trend surfaces were fitted to these elevation values. Computer-generated maps in Figure 40 show these surfaces. Statistical evaluation of all

DE
650


800
DI
700
650

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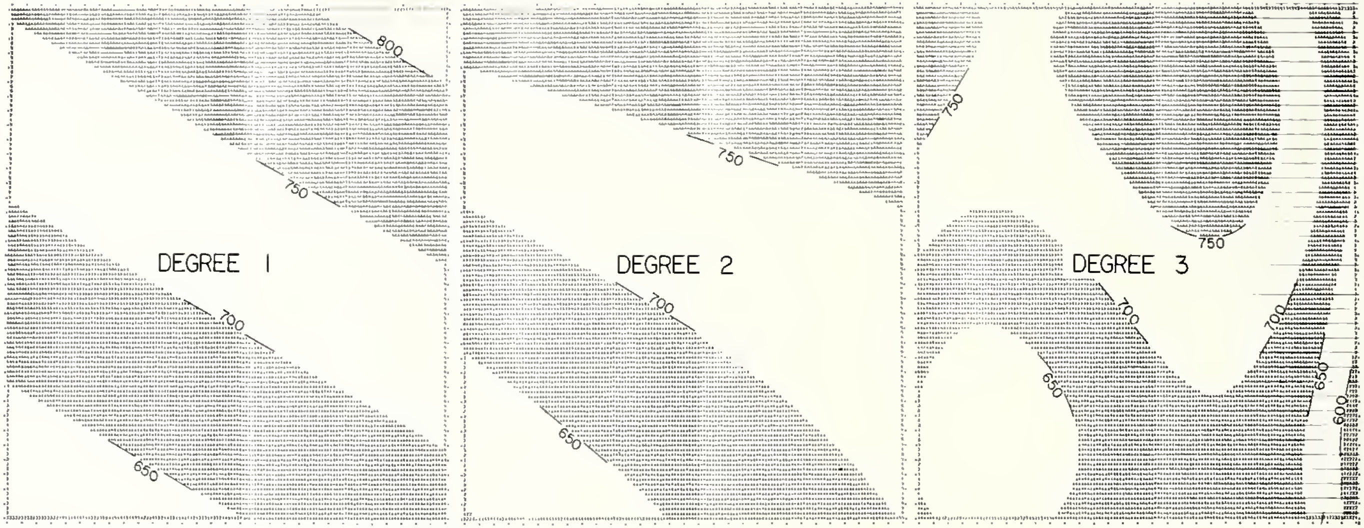


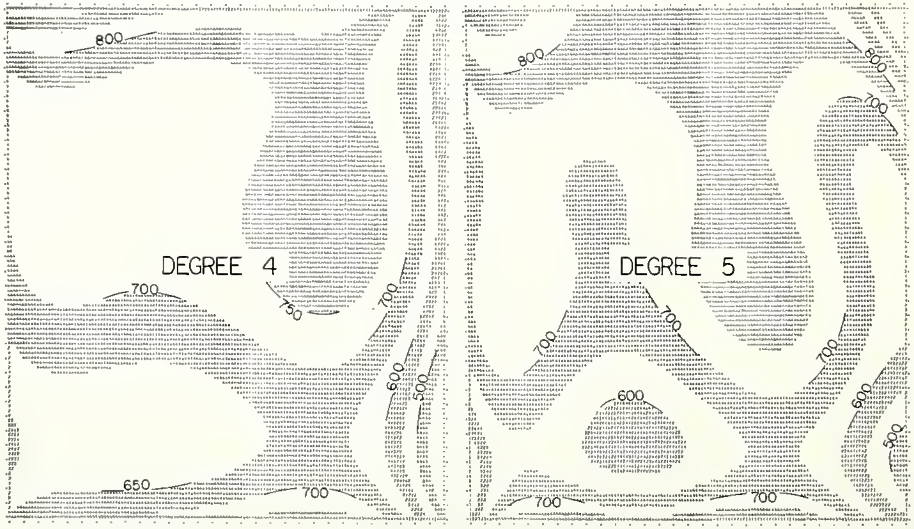
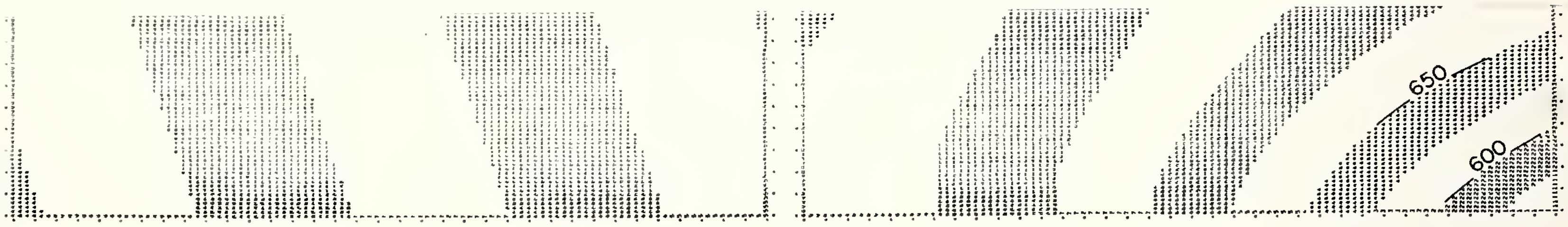


FIGURE 40.

SOUTHERN TEST AREA
COMPUTER-GENERATED CONTOUR
MAPS OF
TREND SURFACES OF DEGREE
ONE THROUGH FIVE
FOR
TOPOGRAPHIC ELEVATIONS
FROM 1:250,000 SCALE MAPS.

SCALE
0 5 10 15 20 MILE

TREND SURFACE	CONTOUR INTERVAL	PERCENT VARIATION EXPLAINED
DEGREE 1	50 feet	15.6
DEGREE 2	50 feet	15.9
DEGREE 3	50 feet	18.5
DEGREE 4	50 feet	24.9
DEGREE 5	50 feet	30.8


650
600

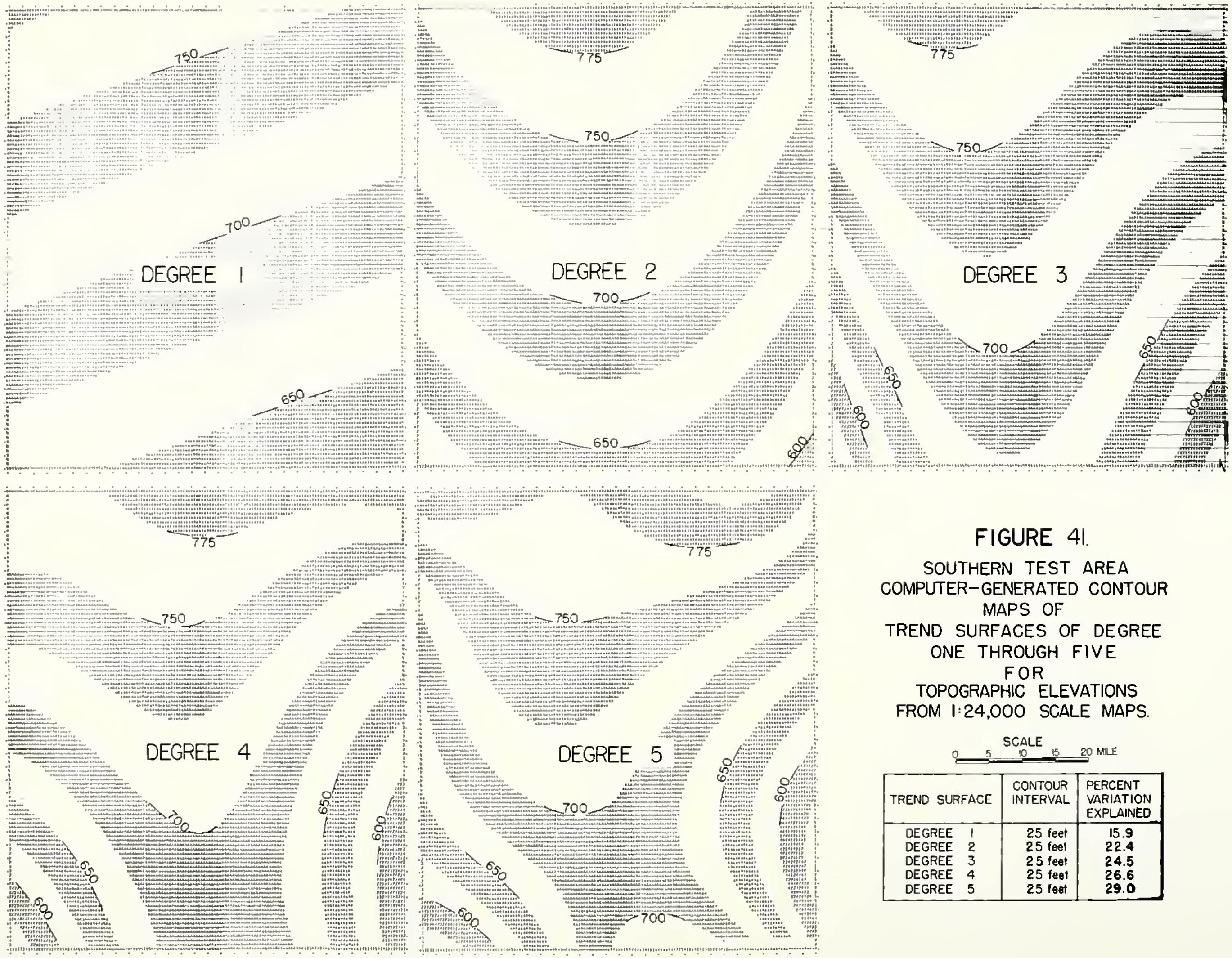


FIGURE 41.

SOUTHERN TEST AREA
COMPUTER-GENERATED CONTOUR
MAPS OF
TREND SURFACES OF DEGREE
ONE THROUGH FIVE
FOR
TOPOGRAPHIC ELEVATIONS
FROM 1:24,000 SCALE MAPS.

SCALE
0 5 10 15 20 MILE

TREND SURFACE	CONTOUR INTERVAL	PERCENT VARIATION EXPLAINED
DEGREE 1	25 feet	15.9
DEGREE 2	25 feet	22.4
DEGREE 3	25 feet	24.5
DEGREE 4	25 feet	26.6
DEGREE 5	25 feet	29.0

surfaces was also performed; the results are shown in Table 6.

The first degree trend surface slopes from northeast to southwest. The second degree surface differs only slightly from the first degree surface. Both explain between 15.5 and 16.0 percent of the original variability in the data. The partial F-test shows the second degree coefficients to be significantly different to zero with a confidence of less than 70 percent.

The third degree trend surface has high elevations in the north central map area with a ridge extending north-south. Along the eastern edge and in the southwest lower elevations are found. These patterns appear to reflect the actual topographic conditions as shown in Figure 25. The central ridge corresponds to the Norman Upland, the eastern low to the Scottsburg Lowland, and the southwestern low to the valley of the East Fork White River crossing the Mitchell Plain. These characteristics become better defined in the fourth and fifth degree trend surfaces. The fifth degree surface shows a western band of higher elevations corresponding to the Crawford Upland, a north-south trending zone of lower elevations corresponding to the Mitchell Plain, a second zone of higher elevations corresponding to the Norman Upland, and an eastern zone of low elevations corresponding to the Scottsburg Lowland. The fifth degree trend surface explains about 30 percent of the variability of the data.

Figure 41 shows the results of the trend surface analysis of 10,591 elevation values measured from 72 quadrangles (see Figure 23) which lie within the test area. Each quadrangle was sampled with about 150 points. These were located with respect to origins at the lower left hand corner of each map. The coordinates were transformed to latitude and longitude

TABLE 6

SOUTHERN TEST AREA - RESULTS OF STATISTICAL ANALYSES - I

Values or Measures	Degree of Trend Surface	Analysis of Variance						
			Total F-Tests			Partial F-Tests of Highest Degree Trend		
		Percent Variation Explained	Degrees of Freedom	Computed F-Value	Level of Significance (1-α)	Degrees of Freedom	Computed F-Value	Level of Significance (1-α)
Elevations from 1:250,000 Scale Topographic Maps	1	15.6	3,896	55.2	.99	2,897	98.5	.99
	2	15.9	6,893	28.2	.99	3,896	1.4	.75
	3	18.5	10,889	20.2	.99	4,895	8.4	.99
	4	24.9	15,884	19.6	.99	5,894	16.2	.99
	5	30.5	21,878	18.3	.99	6,893	11.6	.99
Elevations from all (72) 1:24,000 Scale Topographic Maps	1	15.9	3,10587	670.8	.99	2,10588	1189.0	.99
	2	22.4	6,10584	510.2	.99	3,10587	320.7	.99
	3	24.5	10,10580	342.8	.99	4,10586	75.9	.99
	4	26.6	15,10575	255.1	.99	5,10585	62.5	.99
	5	29.0	21,10569	205.7	.99	6,10584	60.6	.99
Elevations from 1:24,000 Scale Topographic Maps in Northwest Quarter	1	5.5	3,3537	68.3	.99	2,3538	130.4	.99
	2	8.7	6,3534	56.3	.99	3,3537	51.7	.99
	3	17.3	10,3530	73.9	.99	4,3536	102.2	.99
	4	19.2	15,3525	56.0	.99	5,3535	18.4	.99
	5	26.2	21,3519	59.4	.99	6,3534	55.1	.99
Elevations from 1:24,000 Scale Topographic Maps in Northeast Quarter	1	11.3	3,3417	145.8	.99	2,3418	367.1	.99
	2	26.8	6,3414	208.4	.99	3,3417	333.6	.99
	3	35.3	10,3410	185.8	.99	4,3416	137.0	.99
	4	42.1	15,3405	165.2	.99	5,3415	88.6	.99
	5	47.5	21,3399	146.3	.99	6,3414	57.8	.99
Elevations from 1:24,000 Scale Topographic Maps in Southwest Quarter	1	11.4	3,3852	165.2	.99	2,3853	319.1	.99
	2	14.6	6,3849	109.5	.99	3,3852	59.3	.99
	3	24.8	10,3845	127.0	.99	4,3851	143.6	.99
	4	28.4	15,3840	101.5	.99	5,3850	39.8	.99
	5	31.5	21,3834	84.1	.99	6,3849	29.3	.99
Elevations from 1:24,000 Scale Topographic Maps in Southeast Quarter	1	16.4	3,3770	246.3	.99	2,3771	560.4	.99
	2	18.7	6,3767	144.5	.99	3,3770	52.9	.99
	3	29.5	10,3763	157.6	.99	4,3769	184.9	.99
	4	35.6	15.3758	138.4	.99	5,3768	83.0	.99
	5	45.1	21,3752	147.0	.99	6,3767	108.8	.99

values before trend surface analysis was undertaken. The trend surfaces are somewhat different to those obtained from the analysis of the 1:250,000 scale maps. The first degree surface slopes to the southeast rather than to the southwest as in the previous analysis. The second degree surface is significantly different. An area of high elevations is found in the center of the northern edge of the area and a parabolic surface slopes from this point. The third, fourth, and fifth degree surfaces progressively refine the characteristics shown by the second degree surface.

The total F-tests showed that all the trend surfaces for both sets of data had coefficients significantly different from zero at high levels of confidence. The partial F-tests showed the individual surface coefficients to be significant, with the exception of the second degree coefficient for the 1:250,000 scale map data. All these statistics are shown in Table 6. However Table 6 also shows that both fifth degree trend surfaces explain only 30 percent of the variability in the original data. It was believed desirable to explain a higher percent variability and so piecewise trend surface fitting was attempted.

The test area was subdivided into four "quarters" which overlapped each other. First through fifth degree trend surfaces were fitted to each area independently and the results analyzed. The statistical evaluations of all twenty trend surfaces are given in Table 6. As a result of careful study it was decided to combine the four fifth degree trend surfaces into a single trend mosaic. Figure 42 shows the four fifth degree trend surfaces. These were combined to form first an eastern and a western half, as shown in Figure 43. These were in turn merged to form

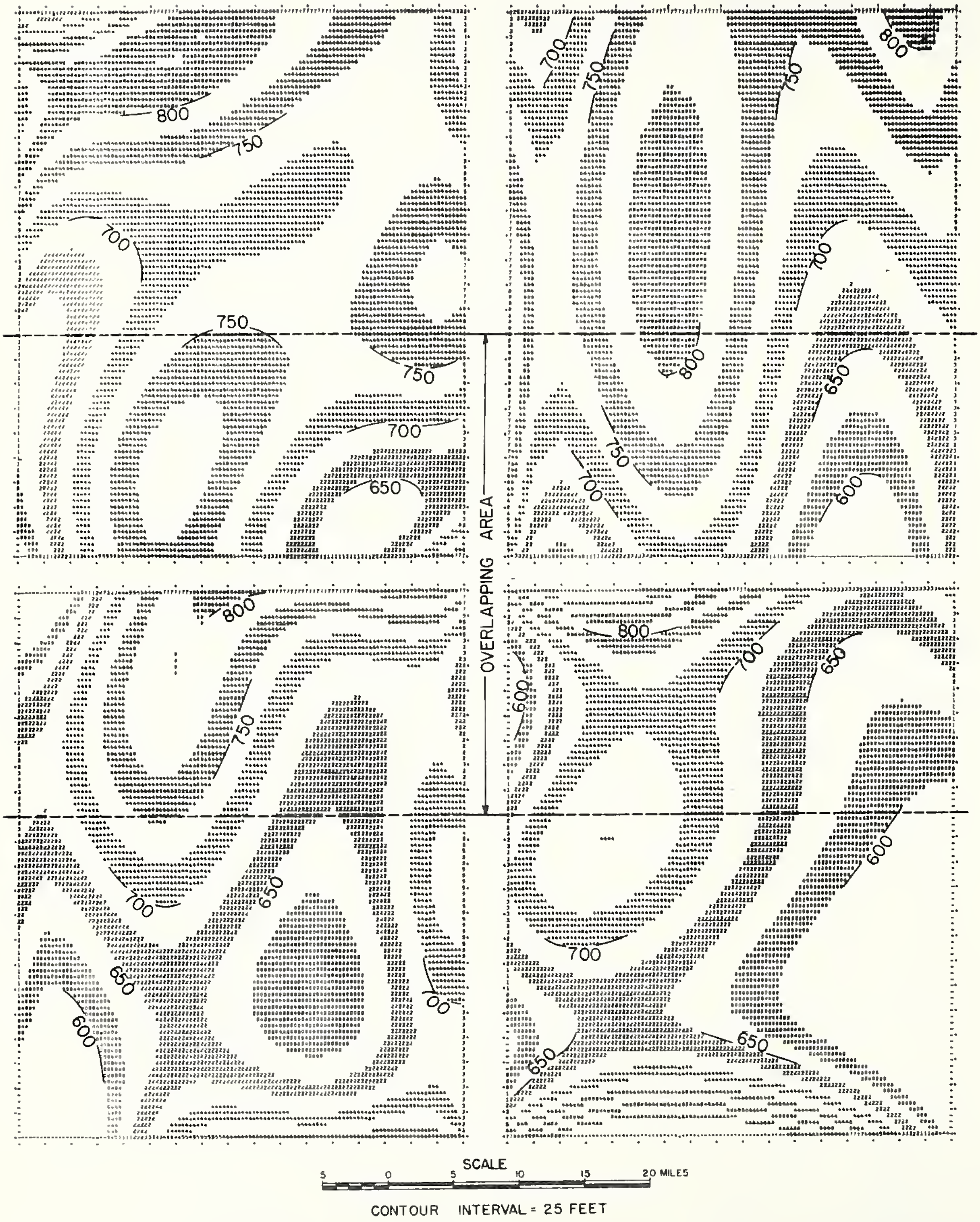


FIGURE 42. PRODUCTION OF A TREND MOSAIC FOR TOPOGRAPHIC DATA - STEP I - FOUR ORIGINAL FIFTH DEGREE TREND SURFACES.

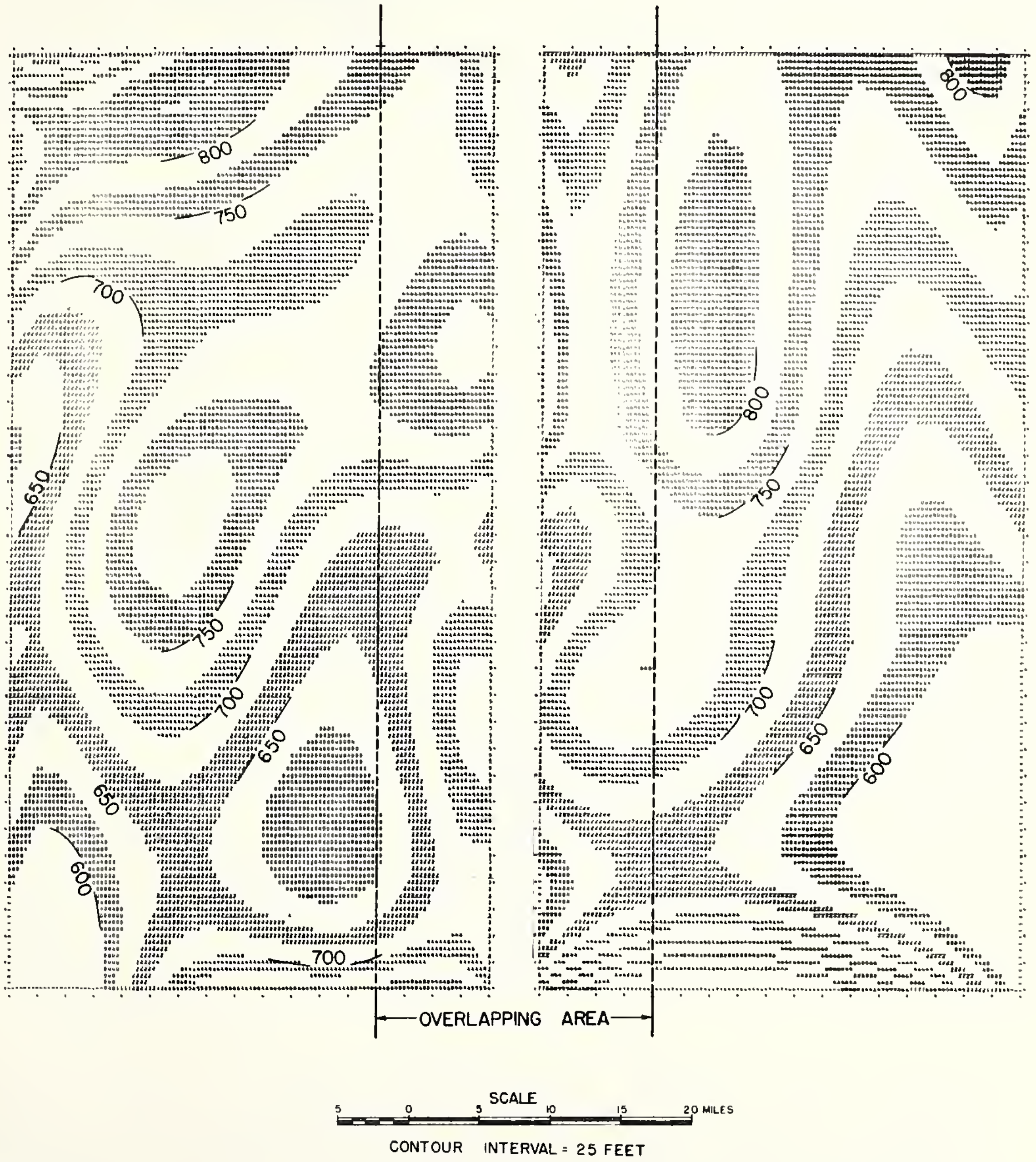
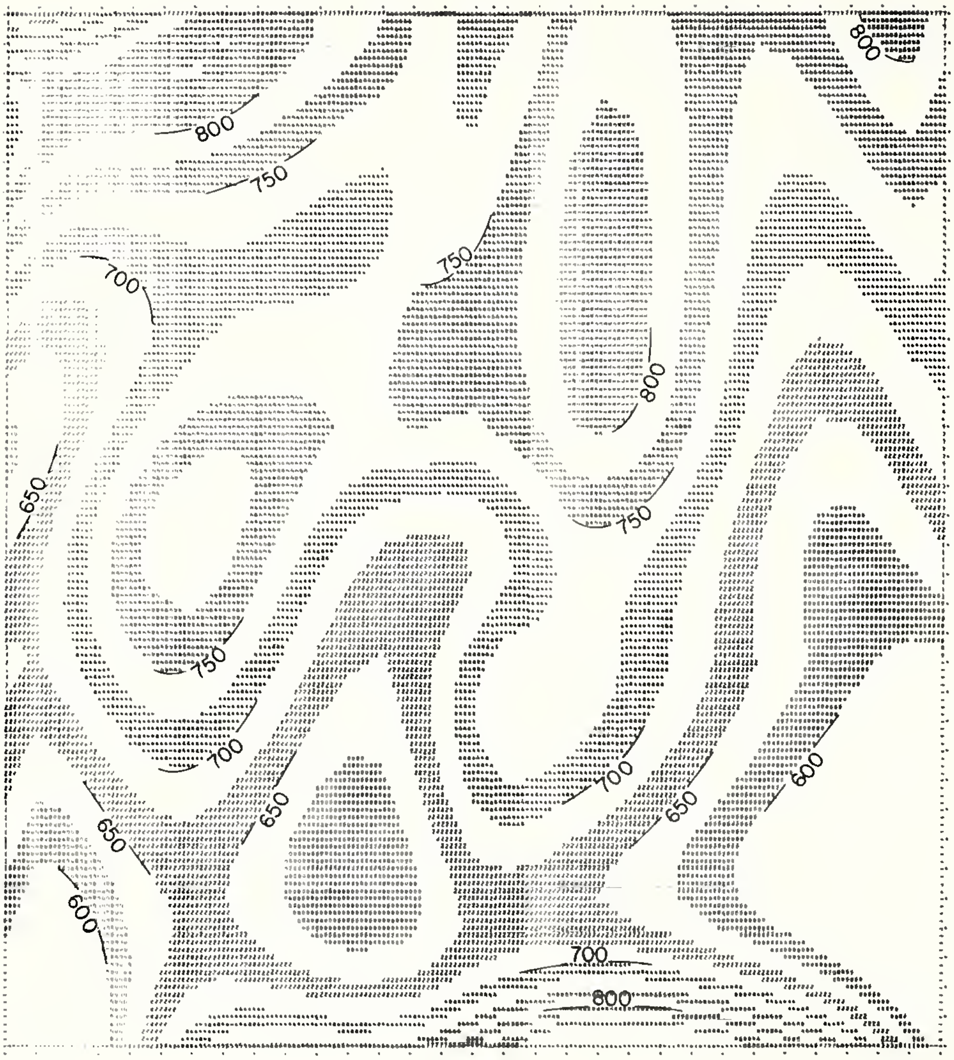
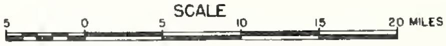


FIGURE 43. PRODUCTION OF A TREND MOSAIC FOR TOPOGRAPHIC DATA -- STEP 2 - EASTERN AND WESTERN TREND SURFACE HALVES FORMED BY MERGING THE SURFACES IN FIGURE 42.





CONTOUR INTERVAL = 25 FEET

FIGURE 44. PRODUCTION OF A TREND MOSAIC FOR TOPOGRAPHIC DATA – STEP 3 – THE FINAL TREND MOSAIC FORMED BY MERGING THE SURFACES IN FIGURE 43.

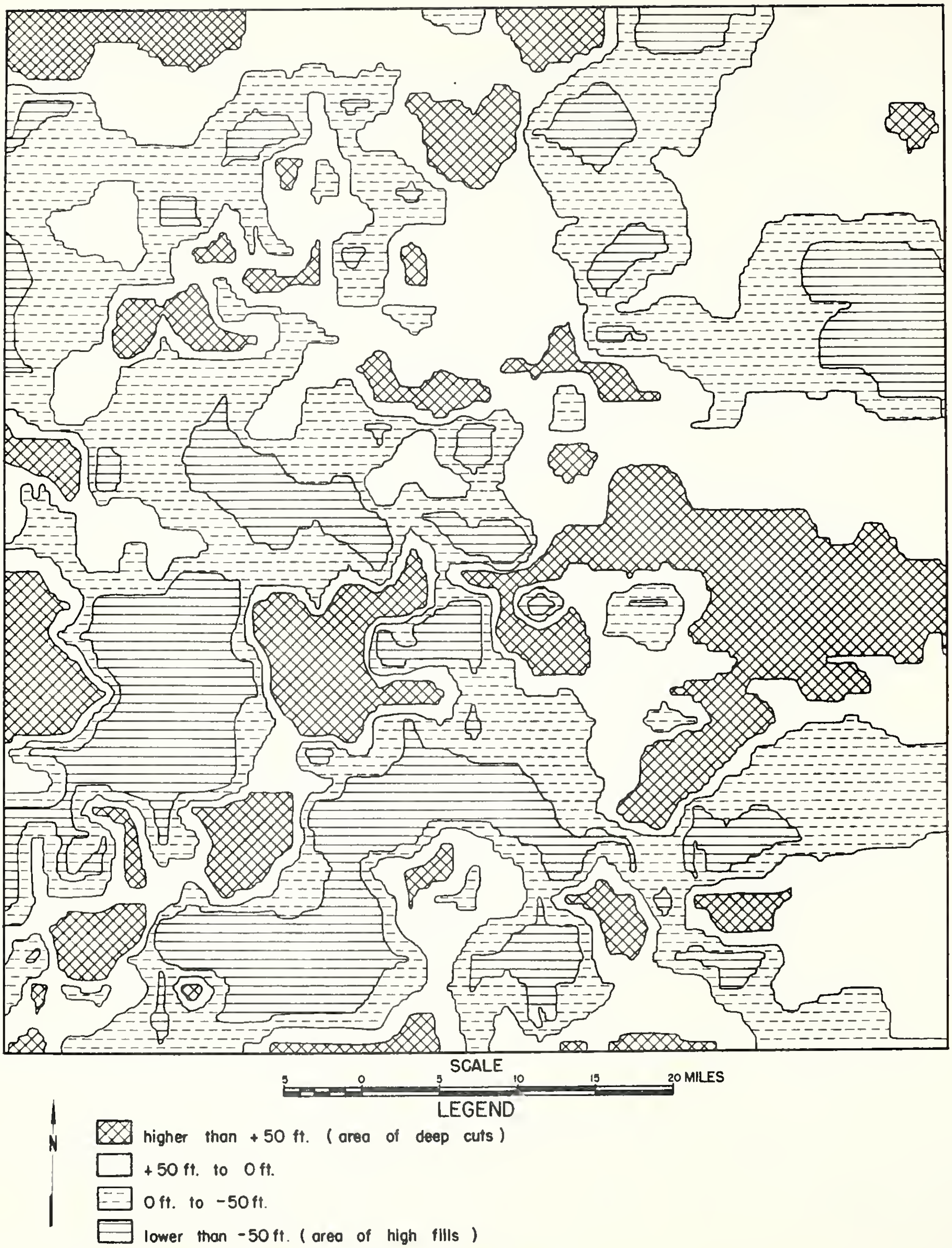
the final trend mosaic shown in Figure 44. The merging was accomplished by simple weighted avarage calculations at a series of points within the overlapping areas. The approximate percent variability explained by the trend mosaic can be estimated by the average of the percent variations explained by each of the quarter trend surfaces. This value is 37.5 percent.

Residuals to the mosaic trend surface and to each of the overall fifth degree trend surfaces were calculated for a series of grid points at roughly a two mile spacing using a weighted moving average algorithm [113]. Maps of these residual values are shown in Figure 45, 46, and 47. Each of these data sets was used as a value of the earthwork cost factor.

Derivation of a Value Surface for the Pavement Construction Cost Factor

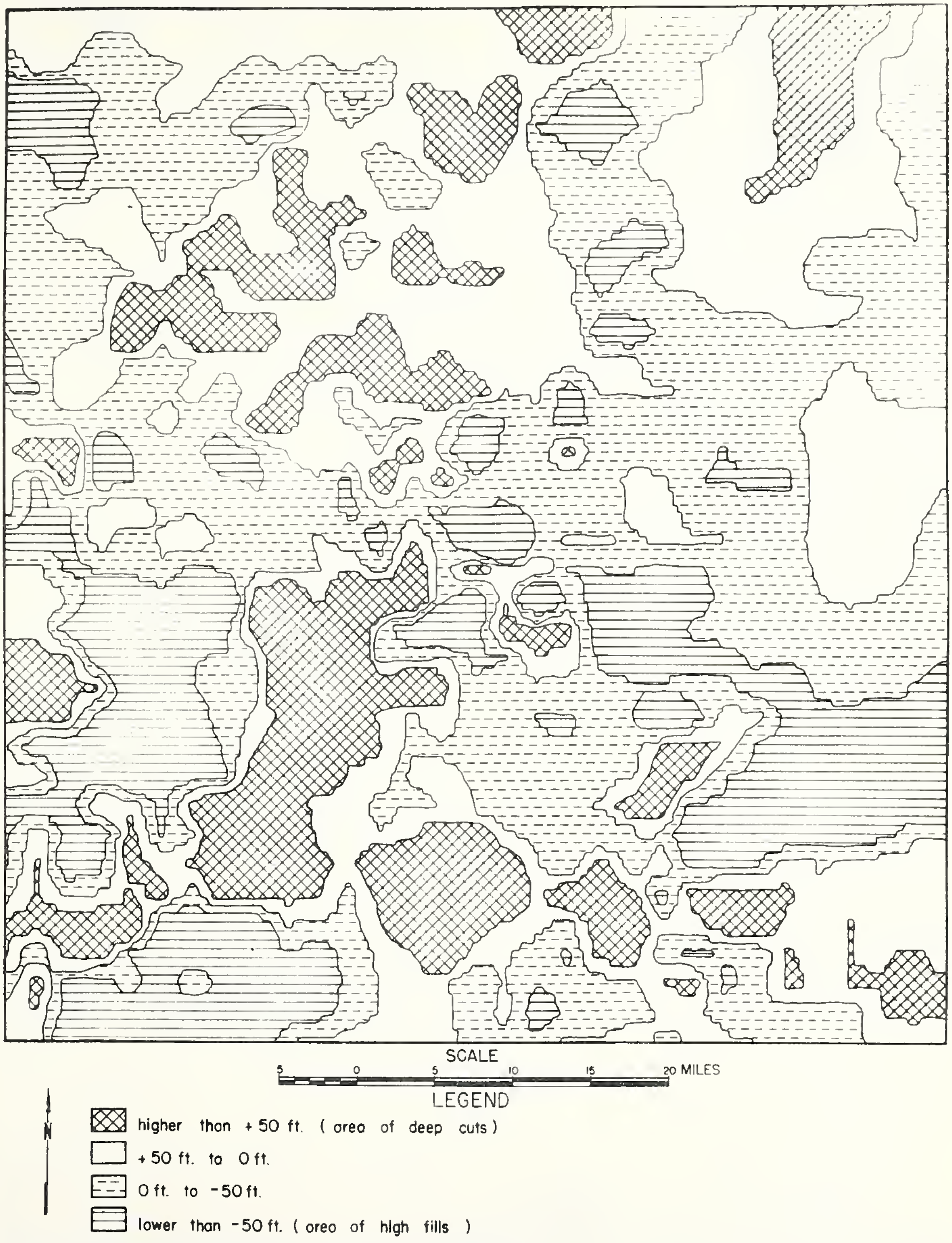
Information on the distribution of soil types within the southern test area was obtained from a state wide engineering soils map developed by Belcher, Gregg, and Woods [10]. A photographic enlargement of this map at a scale of one inch to four miles was obtained from the Indiana State Highway Commission. Figure 26 (page 105) shows a redrawn portion of this map covering the southern test area.

Twelve soil types were mapped within the test area. Each was given a code number and the map was digitized according to the procedures outlined for homogeneous discontinuous measures in Chapter IV. A total of 1328 sample points were required. In order to transform these soil code numbers to values of the pavement construction cost factor, a suitable valuation procedure had to be developed. Research performed at Purdue University by Ulbricht supplied data on the relative merits of the


SCALE
5
0
5
10
15
20 MILES
LEGEND
N
higher than + 50 ft. (area of deep cuts)
+ 50 ft. to 0 ft.
0 ft. to − 50 ft.
lower than − 50 ft. (area of high fills)

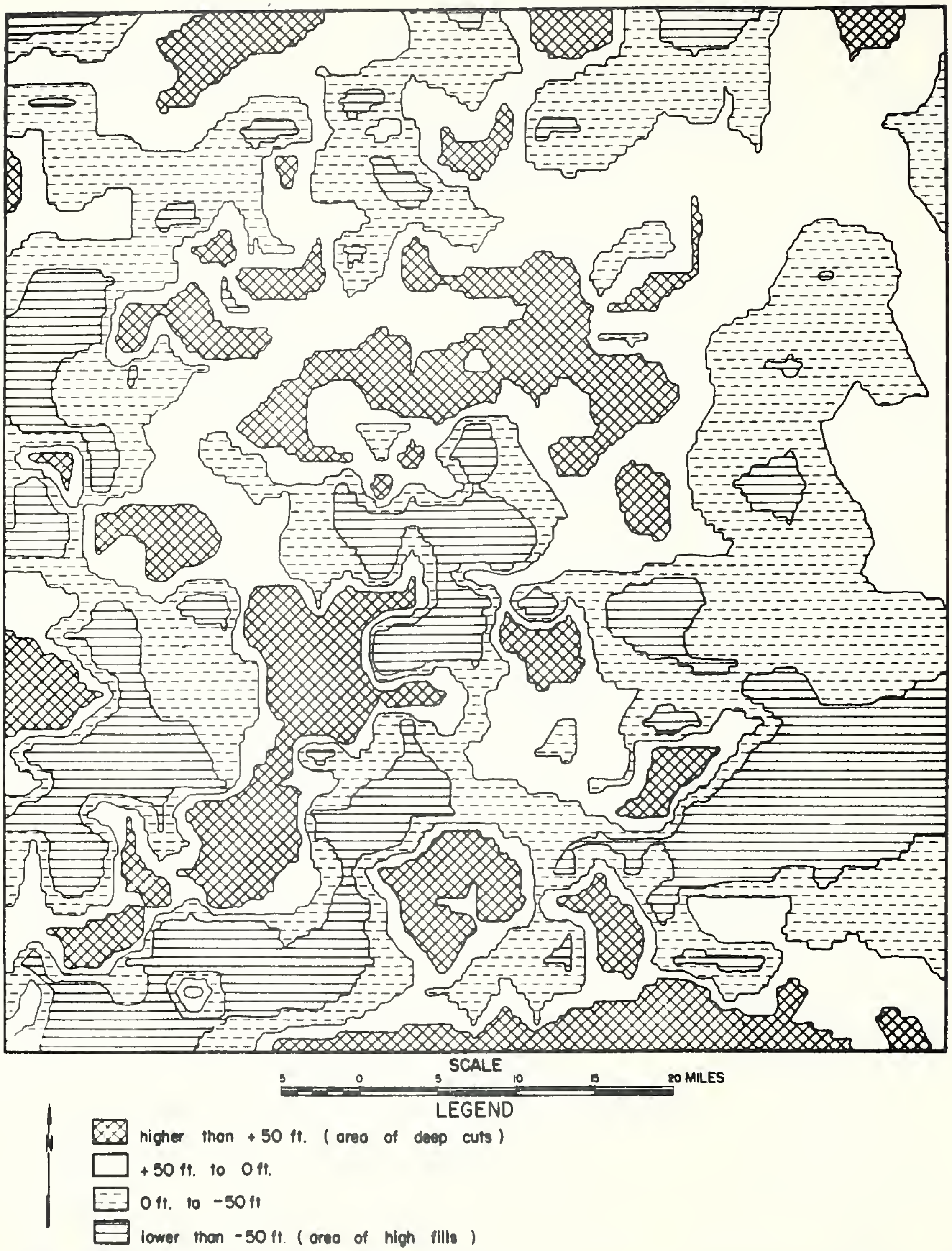
Note :- Map traced from computer - generated printer map.

FIGURE 45. SOUTHERN TEST AREA - MAP OF RESIDUALS TO FIFTH DEGREE TREND SURFACE FITTED TO ELEVATIONS FROM 1:250,000 SCALE TOPOGRAPHIC MAPS.


SCALE
5
0
5
10
15
20 MILES
LEGEND
N
higher than + 50 ft. (area of deep cuts)
+ 50 ft. to 0 ft.
0 ft. to - 50 ft.
lower than - 50 ft. (area of high fills)

Note :- Map traced from computer - generated printer map.

FIGURE 46. SOUTHERN TEST AREA - MAP OF RESIDUALS TO FIFTH DEGREE TREND SURFACE FITTED TO ELEVATIONS FROM ALL 1:24000 SCALE TOPOGRAPHIC MAPS.


SCALE
5 0 5 10 15 20 MILES
LEGEND
higher than + 50 ft. (area of deep cuts)
+ 50 ft. to 0 ft.
0 ft. to - 50 ft
lower than - 50 ft. (area of high fills)

Note :- Map traced from computer - generated printer map.

FIGURE 47. SOUTHERN TEST AREA - MAP OF RESIDUALS TO FIFTH DEGREE MOSAIC TREND SURFACE.

different soil types [118].

Ulbricht studied methods for comparing alternate pavement designs. By using 160 pavement study sections throughout the state of Indiana, he showed that the AASHO Performance Equations developed from the AASHO Test Road data gave acceptably precise predictions of pavement performance. These equations estimate the decrease in road quality in relation to the number of equivalent wheel loads applied, taking into account the soil conditions over which the road is built, and the pavement design.

By using a panel of six experienced engineers, Ulbricht developed a mean soil rating for each soil type shown on the statewide engineering soil map, based on a ten point soil rating scheme. Ulbricht was able to show that these mean soil ratings were proportional to the soil support factors required by the AASHO design equations. Thus larger ratings meant larger soil support factors, greater equivalent pavement thicknesses, and longer pavement life for any pavement design under a given traffic condition. Alternatively, if a standardized useful pavement life is desired, cheaper, thinner, pavements can be built on soils having higher ratings.

Ulbricht's mean ratings are on a ten point scale in which high values are assigned to desirable soils. It is necessary to subtract these ratings from ten to obtain pavement construction cost values that are large for poor soils and small for good ones. A rating scheme for soil categories was developed by Hoffman and Fleckenstein [42] for New York state. Their ratings were based on construction records of the New York Thruway and include only eight categories. Comparison of the two scales showed them to be quite comparable. However, since Ulbricht's data were developed in Indiana, and were more detailed, it was decided to utilize these data in this project.

Table 7 shows the values assigned to each soil category. Two categories shown on the soils map were not separately rated by Ulbricht. These were compound soils composed of thin deposits of Illinoian drift overlying residual soils and bedrock. Their ratings were computed as the average of the ratings for Illinoian ground moraine and the appropriate residual soil category.

Trend surfaces of degree one through five were fitted to the pavement cost value data in order to check for sampling bias. Figure 48 shows the computer-generated maps of these trend surfaces. While the first and second degree trend surfaces show a low northeasterly dip, the higher degree surfaces show more complex patterns. Statistical evaluations of these surfaces, summarized in Table 8, indicate that their coefficients are all significantly different from zero with high levels of confidence. However, none of these surfaces shows a strong change in value within the area; all the contour intervals on the maps shown in Figure 48 are only 0.25 units. This indicates that there is no strong regional cost difference within the test area. Although areas of low cost soil types do exist, these are mostly small and irregularly scattered over the area. Reference to the engineering soils map shown in Figure 26 and the pavement construction cost values shown in Table 7 reveals that this result is reasonable.

The pavement construction cost value data were accepted as valid. The low percent variation explained by the trend surfaces, only 15.2

TABLE 7

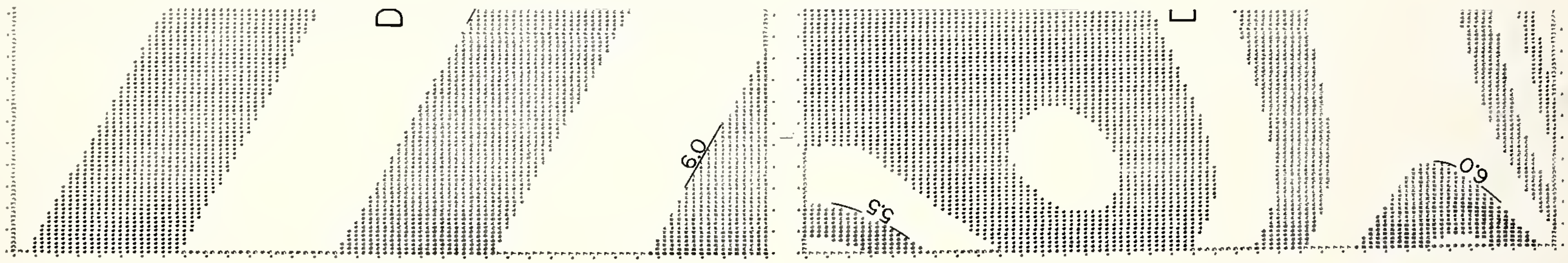
SOUTHERN TEST AREA PAVEMENT CONSTRUCTION COST VALUES

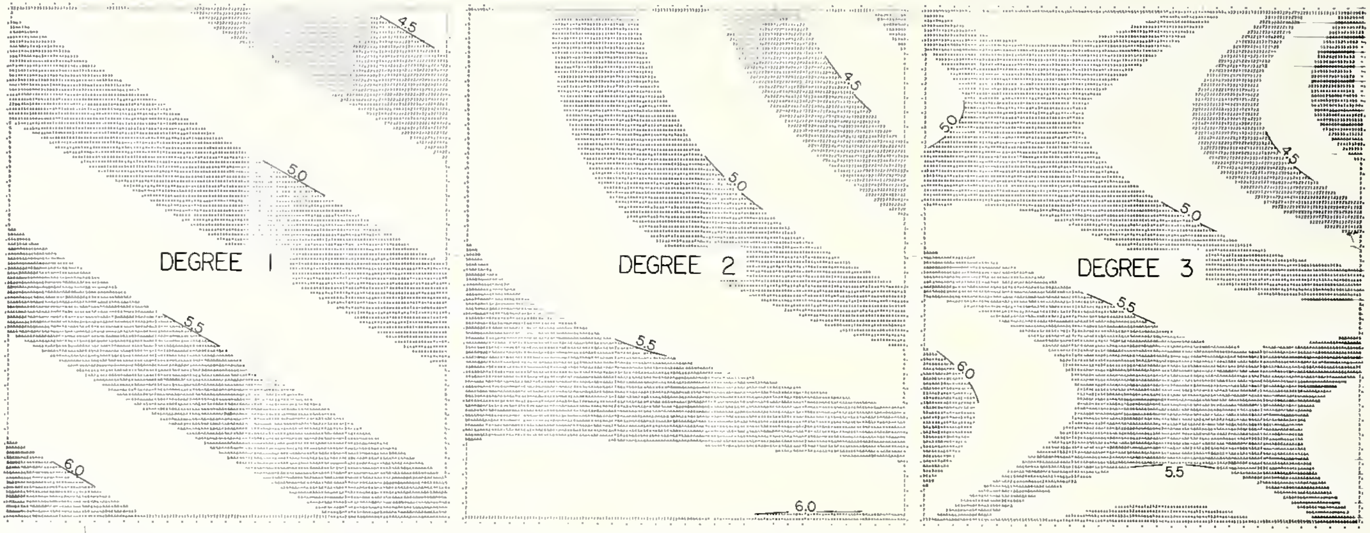
Engineering Soil Type*	Soil Code Number	Ulbricht Mean Rating	Ulbricht Quality Description	Pavement Construction Cost Value***
Outwash Plains	02	8.5	very good	1.5
Sand	03	7.0	good	3.0
Sandstone-Shale Plains	10	5.8	average-good	4.2
Illinoian Ground Moraine over Sandstone-Shale Plains	12	5.3**	average	4.7
Limestone Plains	09	5.1	average	4.9
Illinoian Ground Moraine over Limestone Plains	11	5.0**	average	5.0
Limestone-Sandstone-Shale Plains	08	5.0	average	5.0
Illinoian Ground Moraine	06	4.9	average	5.1
Wisconsin Ridge Moraine	05	4.8	average	5.2
Wisconsin Ground Moraine	04	4.7	average	5.3
Alluvium	01	4.1	average	5.9
Lacustrine Plains	07	3.0	poor	7.0

*Soil categories as identified on Indiana Engineering Soil Map

**Rating not defined by Ulbricht

***Pavement Construction Cost Value = 10.0 - Ulbricht Mean Rating


D
6.0
5.5
6.0



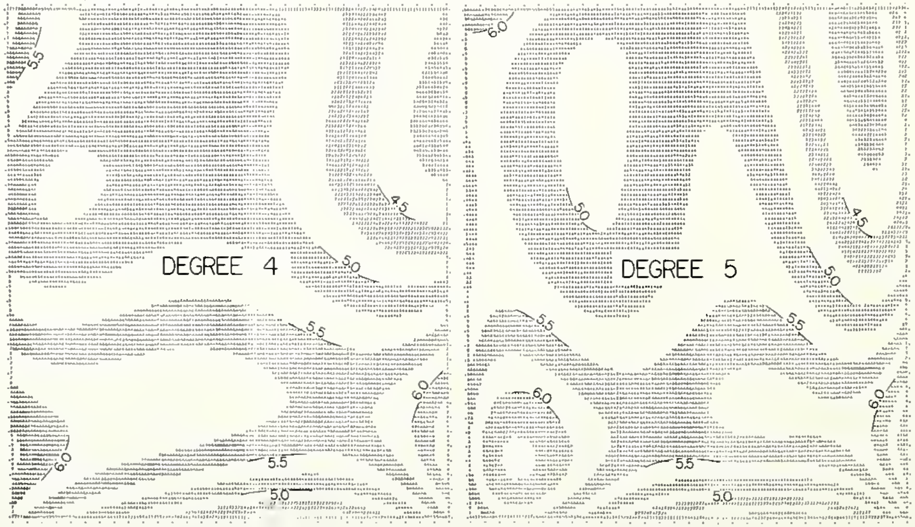


FIGURE 48.

SOUTHERN TEST AREA
COMPUTER-GENERATED CONTOUR
MAPS OF
TREND SURFACES OF DEGREE
ONE THROUGH FIVE
FOR
PAVEMENT CONSTRUCTION
COST VALUES.

SCALE
0 5 10 15 20 MILE

TREND SURFACE	CONTOUR INTERVAL	PERCENT VARIATION EXPLAINED
DEGREE 1	0.25 units	8.4
DEGREE 2	0.25 units	9.4
DEGREE 3	0.25 units	12.0
DEGREE 4	0.25 units	13.6
DEGREE 5	0.25 units	15.2

TABLE 8

SOUTHERN TEST AREA - RESULTS OF STATISTICAL ANALYSES - II

Values or Measures	Degree of Trend Surface	Analysis of Variance						
		Percent Variation Explained	Total F-Tests			Partial F-Tests of Highest Degree Trend		
			Degrees of Freedom	Computed F-Value	Level of Significance (1-α)	Degrees of Freedom	Computed F-Valus	Level of Significance (1-α)
Pavement Construction Cost	1	8.4	3,1324	40.7	.99	2,1325	65.0	.99
	2	9.4	6,1321	22.9	.99	3,1324	5.0	.99
	3	12.0	10,1317	17.9	.99	4,1323	9.9	.99
	4	13.6	15,1312	13.8	.99	5,1322	5.2	.99
	5	15.2	21,1306	11.1	.99	6,1321	4.0	.99
Right of Way Acquisition Cost	1	3.4	3,3662	42.4	.99	2,3663	69.2	.99
	2	4.4	6,3659	27.8	.99	3,3662	13.8	.99
	3	5.8	10,3655	22.4	.99	4,3661	14.5	.99
	4	8.8	15,3650	23.5	.99	5,3660	25.2	.99
	5	11.7	21,3644	22.9	.99	6,3659	19.5	.99
Populstions of Incorporated Towns and Cities	1	0.9	3,37	0.1	.025	2,38	0.2	.10
	2	7.5	6,34	0.5	.10	3,37	0.8	.50
	3	19.2	10,30	0.7	.25	4,36	1.1	.50
	4	31.6	15,25	0.8	.25	5,35	0.9	.50
	5	48.8	21,19	0.9	.25	6,34	1.1	.50
Population Densities	1	4.7	3,251	4.1	.99	2,252	6.5	.99
	2	6.0	6,248	2.6	.975	3,251	1.2	.50
	3	8.0	10,244	2.1	.975	4,250	1.4	.75
	4	10.6	15,239	1.9	.975	5,249	1.4	.75
	5	15.8	21,233	2.1	.99	6,248	2.4	.95
Present Road Network Quality	1	10.1	3,1050	39.4	.99	2,1051	63.4	.99
	2	12.7	6,1047	25.3	.99	3,1050	10.8	.99
	3	13.2	10,1043	15.8	.99	4,1049	1.6	.75
	4	15.7	15,1038	12.9	.99	5,1048	6.2	.99
	5	17.8	21,1032	10.6	.99	6,1047	4.4	.99

percent for the fifth degree surface, and the attitudes of the surfaces indicate that large local heterogeneity exists in the data. Accordingly the trend surfaces cannot be used to predict the pavement construction cost values. A series of gridded estimates of these values were computed using a weighted moving average procedure and used to form the pavement construction cost surface which is shown in Figure 49.

Derivation of a Value Surface for the Right of Way Acquisition Cost Factor

Detailed information on land values was not readily available for the southern test area. It was dediced to prepare a land use map of the entire area and a rating system so as to convert the mapped land use categories to values of the right of way acquisition cost factor. The land use map, shown in Figure 27 (page 106), was prepared by interpretation of the most recently available aerial photographic mosaics. Nine different land use cateogries were identified and mapped on these mosaics. The results were combined to form the final land use map. The land use categories were assigned code numbers and the map was digitized according to the procedures outlined for homogeneous discontinuous measures in Chapter IV. A total of 3666 sample points were utilized.

Table 9 shows the adopted rating scale used to transform the mapped land use categories to values of the right of way acquisition cost factor. The scale was prepared after discussion with several Purdue University staff members and is believed reasonable. Agricultural land values were used as a base, and the values for other land use categories were related to the agricultural land values. High ratings given to certain categories are intended to reflect the undesirability of disturbing them as well as

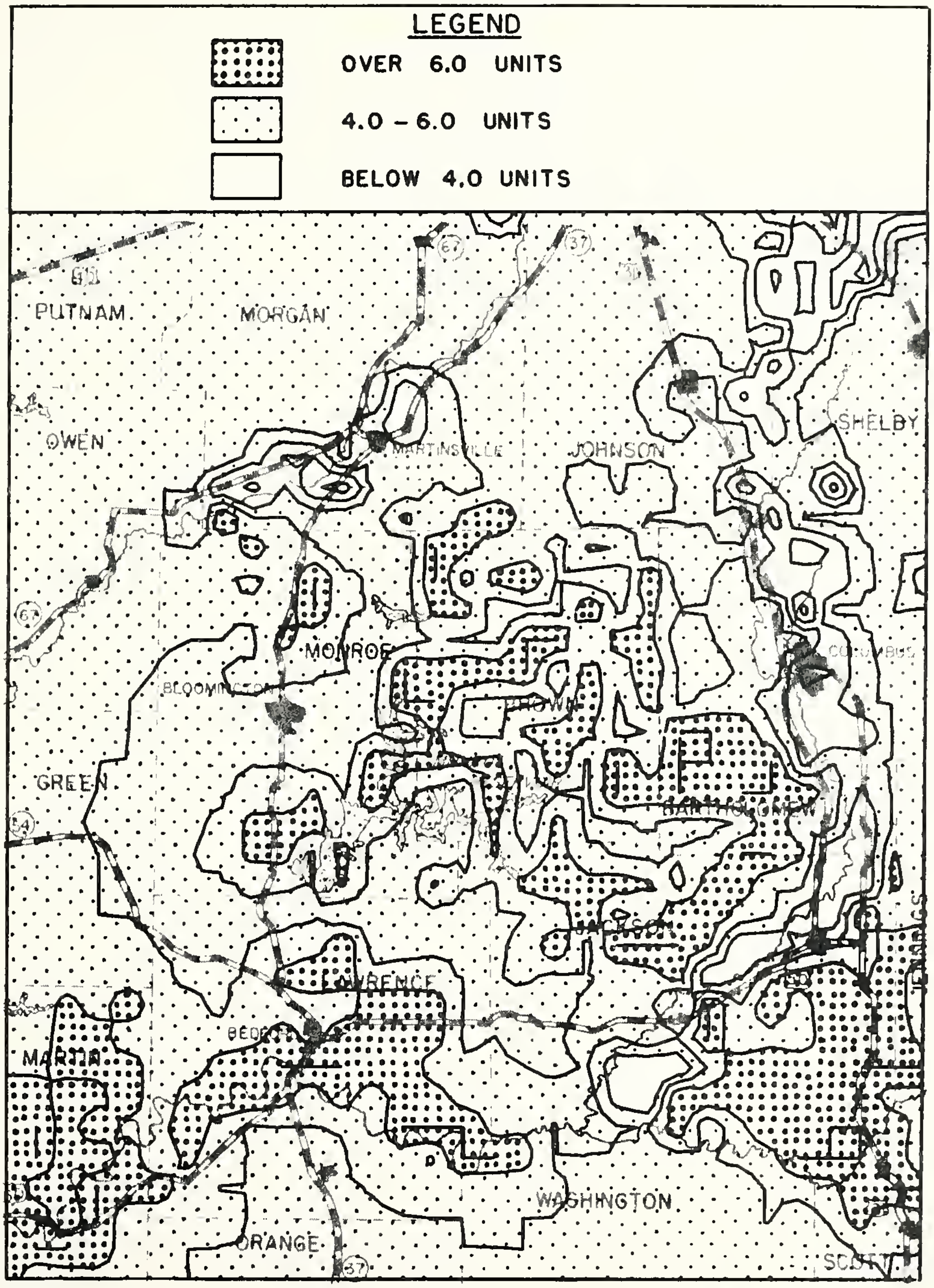


FIGURE 49. SOUTHERN TEST AREA- CONTOUR MAP OF PAVEMENT CONSTRUCTION COST VALUE SURFACE.

TABLE 9

SOUTHERN TEST AREA

ADOPTED RATING SCALE FOR RIGHT OF WAY ACQUISITION COST VALUES

Land Use Category	Code Number	Right of Way Acquisition Cost Value
Forested	01	0.20
Forested with occasional fields	02	0.30
Wooded agricultural	07	0.65
Agricultural	03	1.00
Agricultural with some residential subdivisions	04	3.00
Camp Atterbury Military reserve	09	5.00
Residential and Commercial	05	6.00
Commercial and Industrial	06	8.50
Lakes	08	10.00

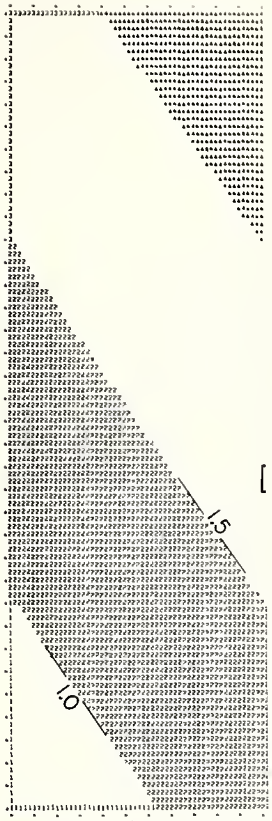
their cost of acquisition.

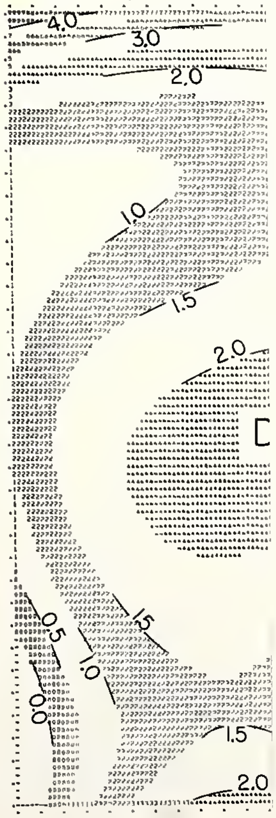
First through fifth degree trend surfaces were fitted to the acquisition cost values to test them for accuracy and lack of bias. Computer generated contour maps of these surfaces are shown in Figure 50. The results of statistical evaluations are shown in Table 8.

The first degree surface slopes downward from the northeast, away from Indianapolis. The second degree surface forms a sloping ridge of high values extending southwest from the Indianapolis area toward Bloomington. It reflects the generally higher land values in the Scottsburg Lowland and near Bloomington.

The third, fourth, and fifth degree surfaces progressively refine their attitudes to more clearly represent actual land values. The fifth degree trend surface has a zone of high values extending southward along the east side of the test area, following the Scottsburg Lowland, and another over the Bloomington-Bedford region. High values extend across the northern edge of the test area while lower values are found in the predominantly forested areas.

Statistical analysis accepts the hypothesis that the trend surface coefficients are significantly different from zero with high levels of confidence. However none of the trend surfaces explain more than 12 percent of the variability inherent in the original data. Thus they are poor predictors of the land values in the area. Accordingly the land value data were estimated at a series of grid points by a weighted moving average technique. These gridded estimates were used to form the right of way acquisition cost value surface. Figure 51 is a contour map of this surface.


1.5
1.0


4.0
3.0
2.0
1.0
1.5
2.0
1.5
0.5
1.0
0.0
1.5
2.0

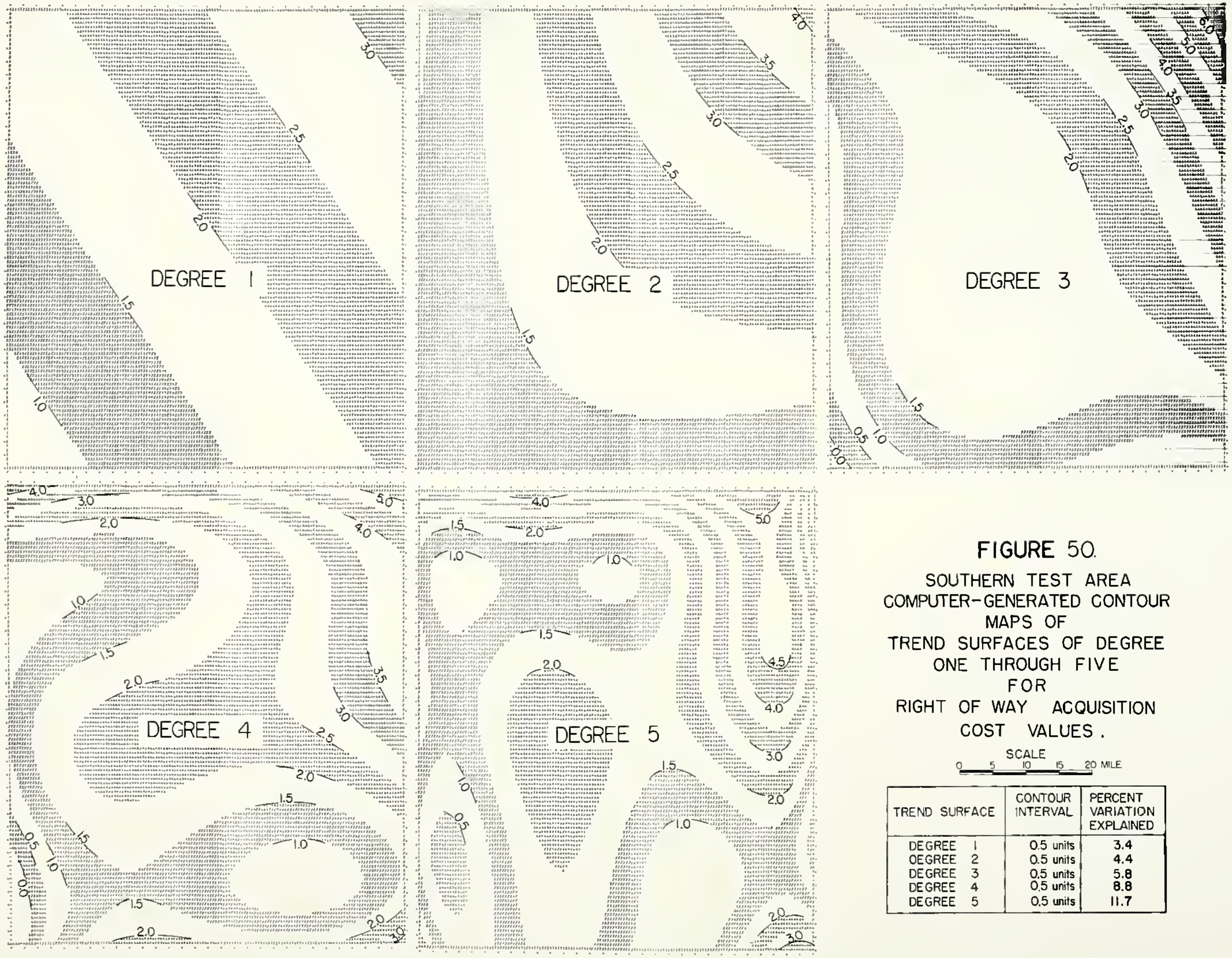


FIGURE 50.

SOUTHERN TEST AREA
COMPUTER-GENERATED CONTOUR
MAPS OF
TREND SURFACES OF DEGREE
ONE THROUGH FIVE
FOR
RIGHT OF WAY ACQUISITION
COST VALUES.

SCALE
0 5 10 15 20 MILE

TREND SURFACE	CONTOUR INTERVAL	PERCENT VARIATION EXPLAINED
DEGREE 1	0.5 units	3.4
DEGREE 2	0.5 units	4.4
DEGREE 3	0.5 units	5.8
DEGREE 4	0.5 units	8.8
DEGREE 5	0.5 units	11.7

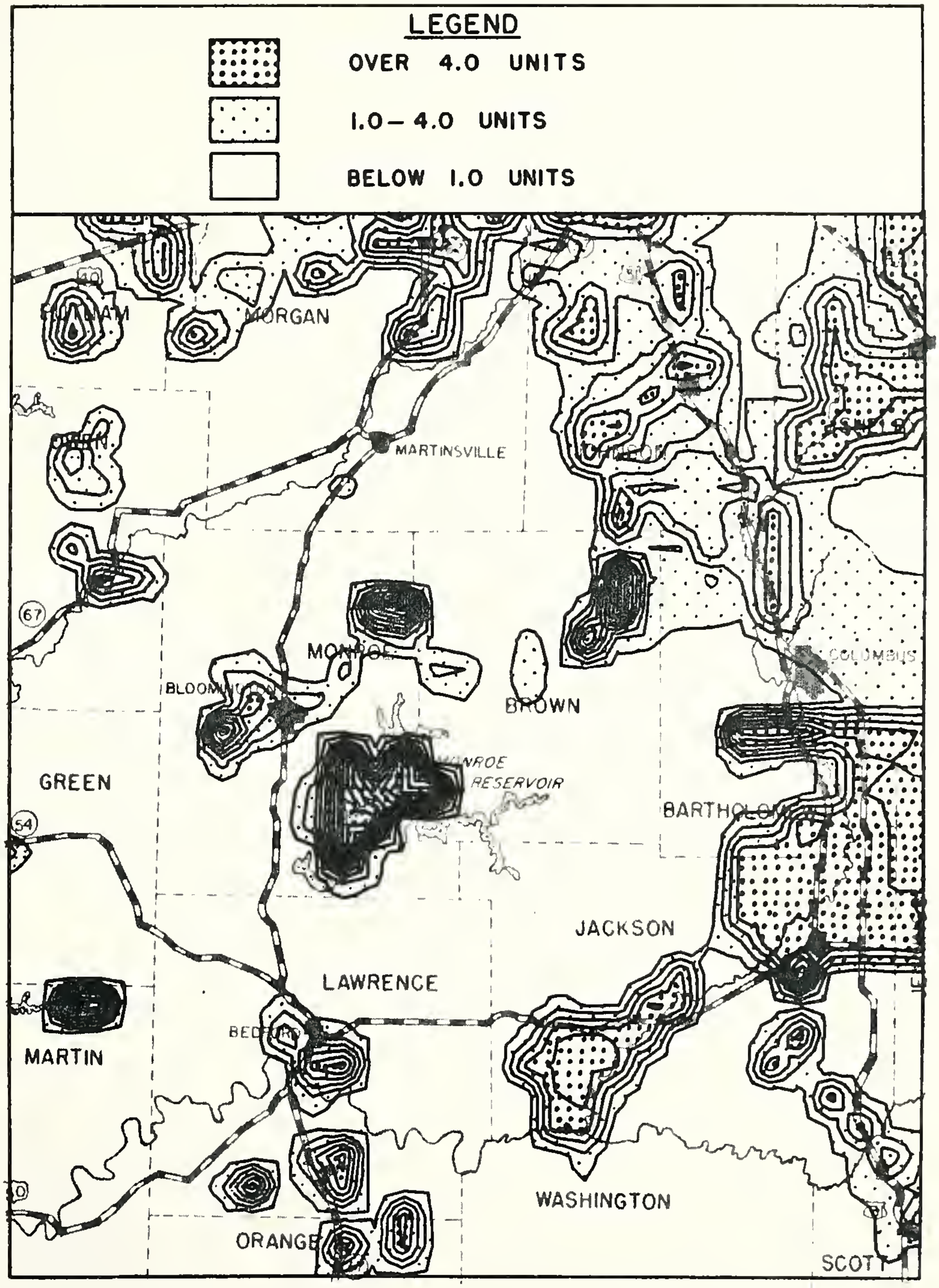


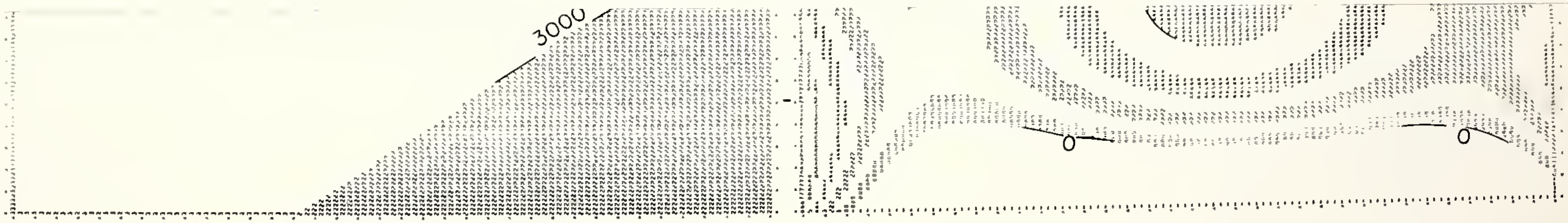
FIGURE 51. SOUTHERN TEST AREA-CONTOUR MAP OF RIGHT OF WAY ACQUISITION COST VALUE SURFACE.

Derivation of Value Surfaces for the Service Benefits Factor

As shown in Table 4, three measures were used to study the service benefit factor in the southern test area. These were (1) the populations of incorporated towns and cities, (2) population densities measured in a series of small areas each covering approximately 20 square miles, and (3) the distribution of present highway facilities.

The populations of all incorporated towns and cities within the test area were obtained from the 1960 census data [11]. A total of 41 such communities lie within the test area. These values were digitized from a 1:250,000 scale map using sampling procedures for discrete measures outlined in Chapter IV.

First through fifth degree trend surfaces were fitted to the data. Maps of these surfaces are shown in Figure 52. The first degree surface slopes downward from northeast to southwest away from the Indianapolis area. The second degree surface is saddle-shaped, with high values in the northeast and southwest and low values in the opposite corners. The higher degree surfaces show high values in the vicinities of the major towns such as Bloomington. Statistical analysis of these surfaces indicates the hypothesis that the coefficients of their equations are different from zero can only be accepted with low confidence. The surfaces do however explain increasing percentages of the variability inherent in the data. These surface shapes have a low reliability because they are based on only 41 observations which are not well distributed. The small number of observations makes it possible to explain almost 50 percent of the variation inherent in the original data with 21 coefficients.


3000
0
0

Derivation of Value Surfaces for the Service Benefits Factor

As shown in Table 4, three measures were used to study the service benefit factor in the southern test area. These were (1) the populations of incorporated towns and cities, (2) population densities measured in a series of small areas each covering approximately 20 square miles, and (3) the distribution of present highway facilities.

The populations of all incorporated towns and cities within the test area were obtained from the 1960 census data [11]. A total of 41 such communities lie within the test area. These values were digitized from a 1:250,000 scale map using sampling procedures for discrete measures outlined in Chapter IV.

First through fifth degree trend surfaces were fitted to the data. Maps of these surfaces are shown in Figure 52. The first degree surface slopes downward from northeast to southwest away from the Indianapolis area. The second degree surface is saddle-shaped, with high values in the northeast and southwest and low values in the opposite corners. The higher degree surfaces show high values in the vicinities of the major towns such as Bloomington. Statistical analysis of these surfaces indicates the hypothesis that the coefficients of their equations are different from zero can only be accepted with low confidence. The surfaces do however explain increasing percentages of the variability inherent in the data. These surface shapes have a low reliability because they are based on only 41 observations which are not well distributed. The small number of observations makes it possible to explain almost 50 percent of the variation inherent in the original data with 21 coefficients.

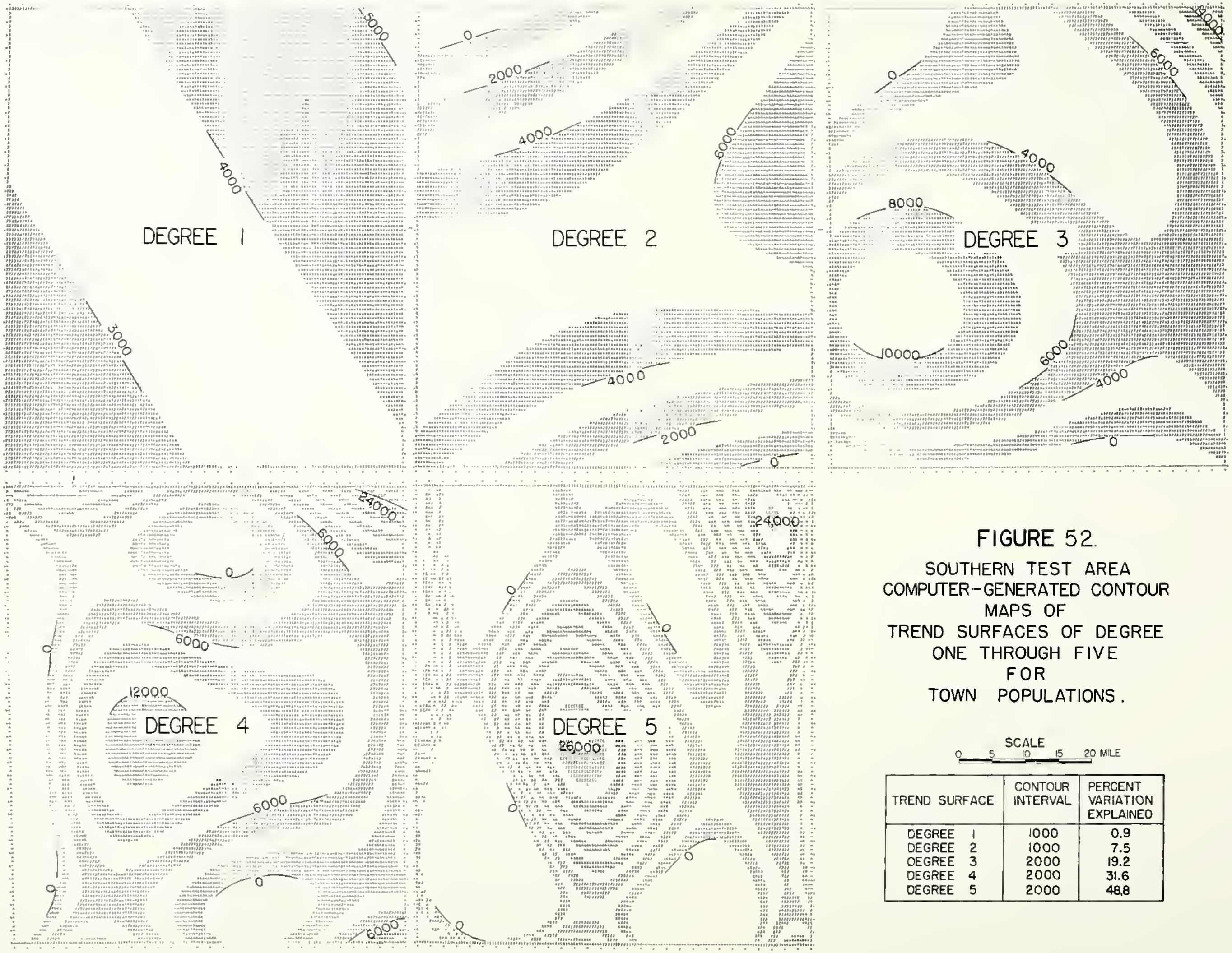


FIGURE 52.

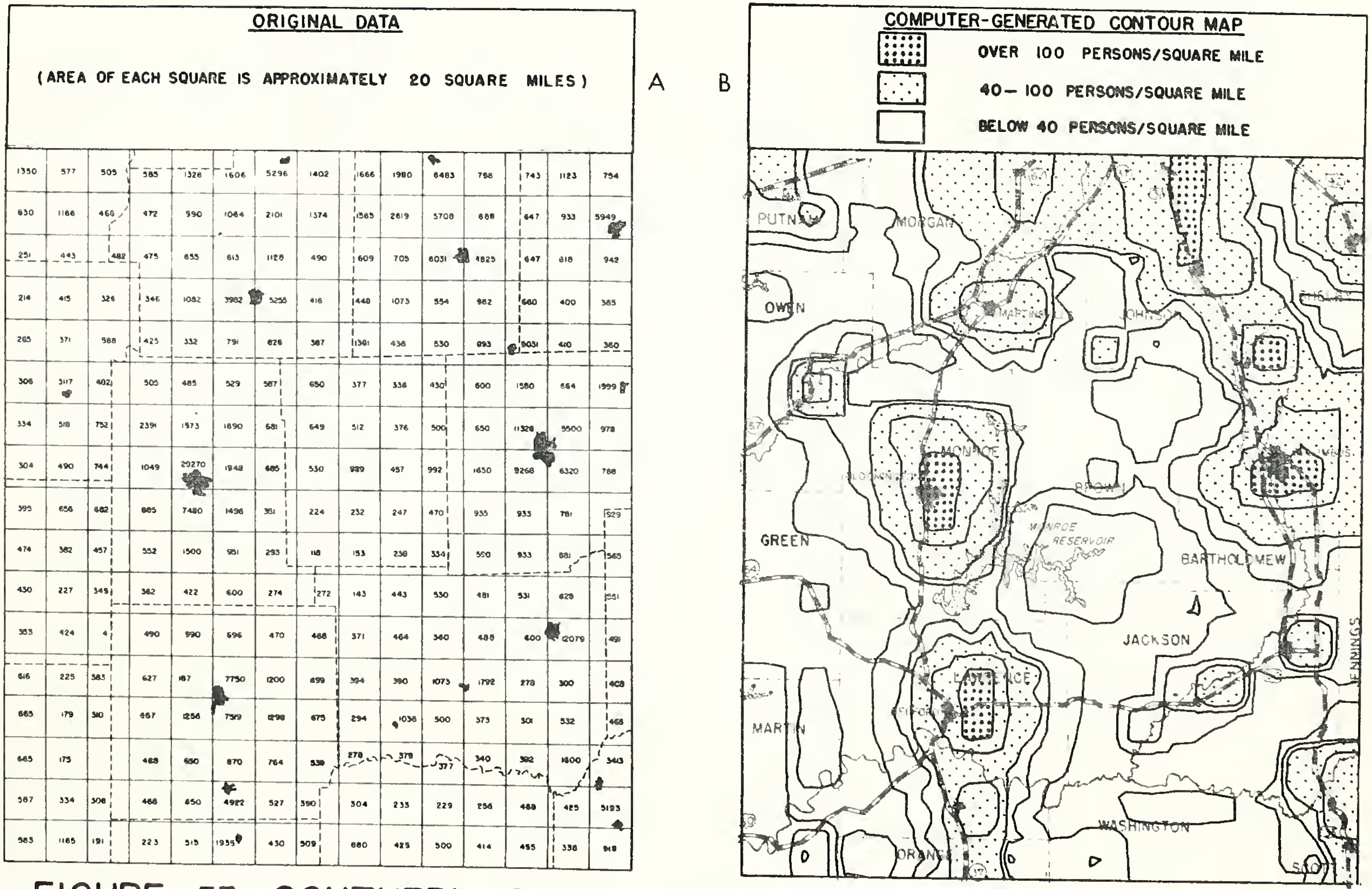
SOUTHERN TEST AREA
COMPUTER-GENERATED CONTOUR
MAPS OF
TREND SURFACES OF DEGREE
ONE THROUGH FIVE
FOR
TOWN POPULATIONS.

SCALE
0 5 10 15 20 MILE

TREND SURFACE	CONTOUR INTERVAL	PERCENT VARIATION EXPLAINED
DEGREE 1	1000	0.9
DEGREE 2	1000	7.5
DEGREE 3	2000	19.2
DEGREE 4	2000	31.6
DEGREE 5	2000	48.8

A population density map was developed in the following manner. Populations for all towns and for all townships within each county are published in the 1960 census reports [11]. Subtraction of urban populations from the appropriate township totals left remainders which were assumed to be rural populations. A series of small areas, each approximately 20 square miles in size, were laid out so as to cover the test area. A population total was calculated for each square which equalled the sum of all urban region populations lying within the square (or portions of urban populations for regions covering more than one square) and a proportion of the rural populations of all townships included within the square. All population values were proportional according to area. Since each square area is of equal size, the totals for each square form a population density distribution. The squares and their totals are shown in Figure 53-A, a contoured version of this data is shown in Figure 53-B.

First through fifth degree trend surfaces were fitted to the population density data. Computer generated maps of these surfaces are shown in Figure 54. The first degree surface slopes downward from the northeast. The second degree surface slopes downward from a high in the northeast to two lows; one on the west and one in the southeast. These are separated by a saddle in the south central part of the test area. The third, fourth, and fifth degree trend surfaces progressively show better approximations to the original data. The fifth degree surface has high values in the northeast which trend southward along the Scottsburg Lowland corridor past Columbus, a high population density corresponding to Bloomington in the southwest, and a lesser high near Martinsville.

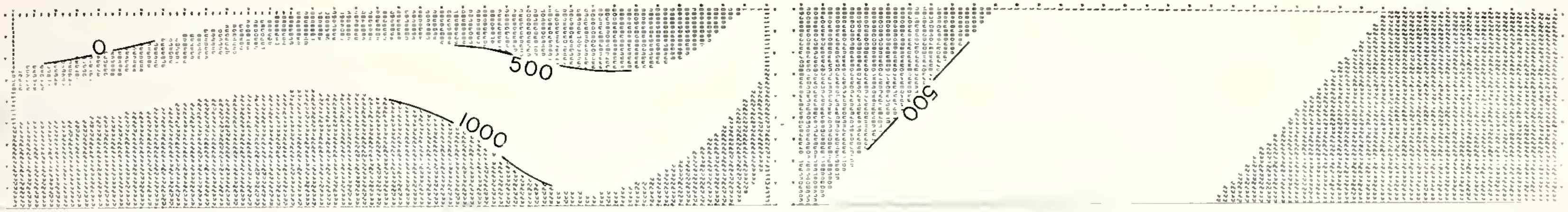


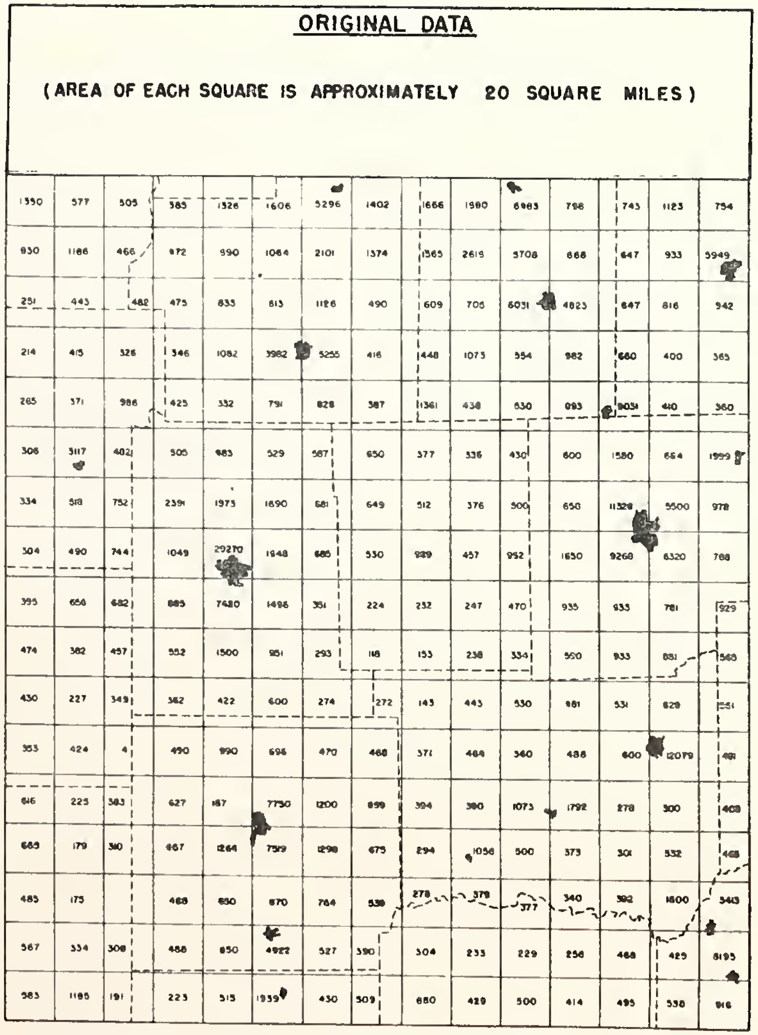
ORIGINAL DATA

(AREA OF EACH SQUARE IS APPROXIMATELY 20 SQUARE MILES)

1350	577	505	585	1326	1606	5296	1402	1666	1980	6483	798	743	1123	794
630	1166	466	472	590	1084	2101	1374	1565	2619	5708	688	647	933	5949
251	443	482	475	655	613	1128	490	609	705	6031	4825	647	618	942
214	415	326	346	1082	3982	5255	416	1448	1073	554	982	680	400	385
265	371	588	425	332	791	826	387	1361	438	530	893	9031	410	360
306	3117	402	505	485	529	587	650	377	338	430	600	1580	664	1999
334	518	752	2391	1573	1690	681	649	512	376	500	650	11328	5500	978
304	490	744	1049	29270	1948	686	530	989	457	992	1650	9268	6320	788
395	656	682	885	7480	1496	381	224	232	247	470	935	933	781	529
474	382	457	552	1500	981	293	118	153	238	334	550	933	881	565
430	227	349	382	422	600	274	272	143	443	530	481	531	828	551
353	424	4	490	990	696	470	488	371	464	360	488	600	12079	491
616	225	383	627	187	7750	1200	899	394	390	1073	1792	278	300	408
885	179	310	457	1256	7519	1298	675	294	1036	500	373	301	532	468
665	175		488	650	870	764	539	278	378	377	340	392	1600	343
587	334	306	488	850	4922	527	390	304	233	229	256	488	425	5193
583	1165	191	223	515	1959	430	509	880	425	500	414	455	338	918

FIGURE 53. SOUTHERN TEST AREA- POPULATION DENSITY DATA.


0
500
1000
500



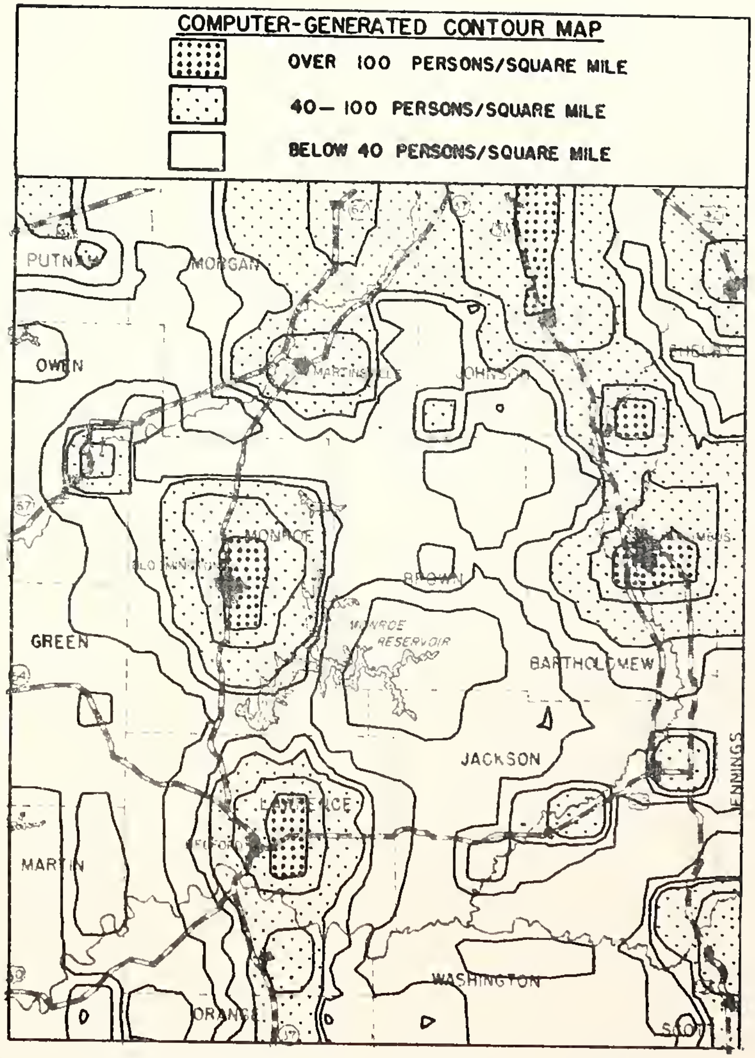
A

ORIGINAL DATA

(AREA OF EACH SQUARE IS APPROXIMATELY 20 SQUARE MILES)

1350	577	505	385	1326	1606	5296	1402	1666	1980	6983	798	743	1123	754
930	1166	466	972	990	1064	2101	1374	1565	2619	5708	668	647	933	5949
251	443	482	475	833	813	1126	490	609	705	6031	4823	647	816	942
214	415	326	346	1082	3982	5255	416	1448	1073	554	982	660	400	365
265	371	986	425	332	791	828	387	1361	438	630	893	9031	410	360
306	3117	402	505	983	529	587	650	377	336	430	600	1580	664	1999
334	518	752	2391	1973	1690	681	649	512	376	500	650	11328	5500	978
304	490	744	1049	29270	1948	685	530	989	457	952	1650	9268	6320	768
395	656	682	885	7420	1496	351	224	232	247	470	935	933	781	929
474	382	457	552	1500	951	293	118	153	238	334	550	933	851	548
430	227	349	362	422	600	274	272	143	443	530	981	531	828	551
353	424	4	490	990	696	470	468	371	484	340	488	600	12079	481
616	225	383	627	187	7750	1200	899	394	380	1073	1792	278	300	408
683	179	310	467	1264	7519	1298	675	294	1056	500	373	301	532	468
485	175		468	880	870	764	538	278	378	377	340	392	1600	3403
567	334	308	488	850	4922	527	390	304	233	229	256	468	429	8195
583	1185	191	223	515	1939	430	509	880	429	500	414	495	538	916

B



COMPUTER-GENERATED CONTOUR MAP

FIGURE 53. SOUTHERN TEST AREA- POPULATION DENSITY DATA.

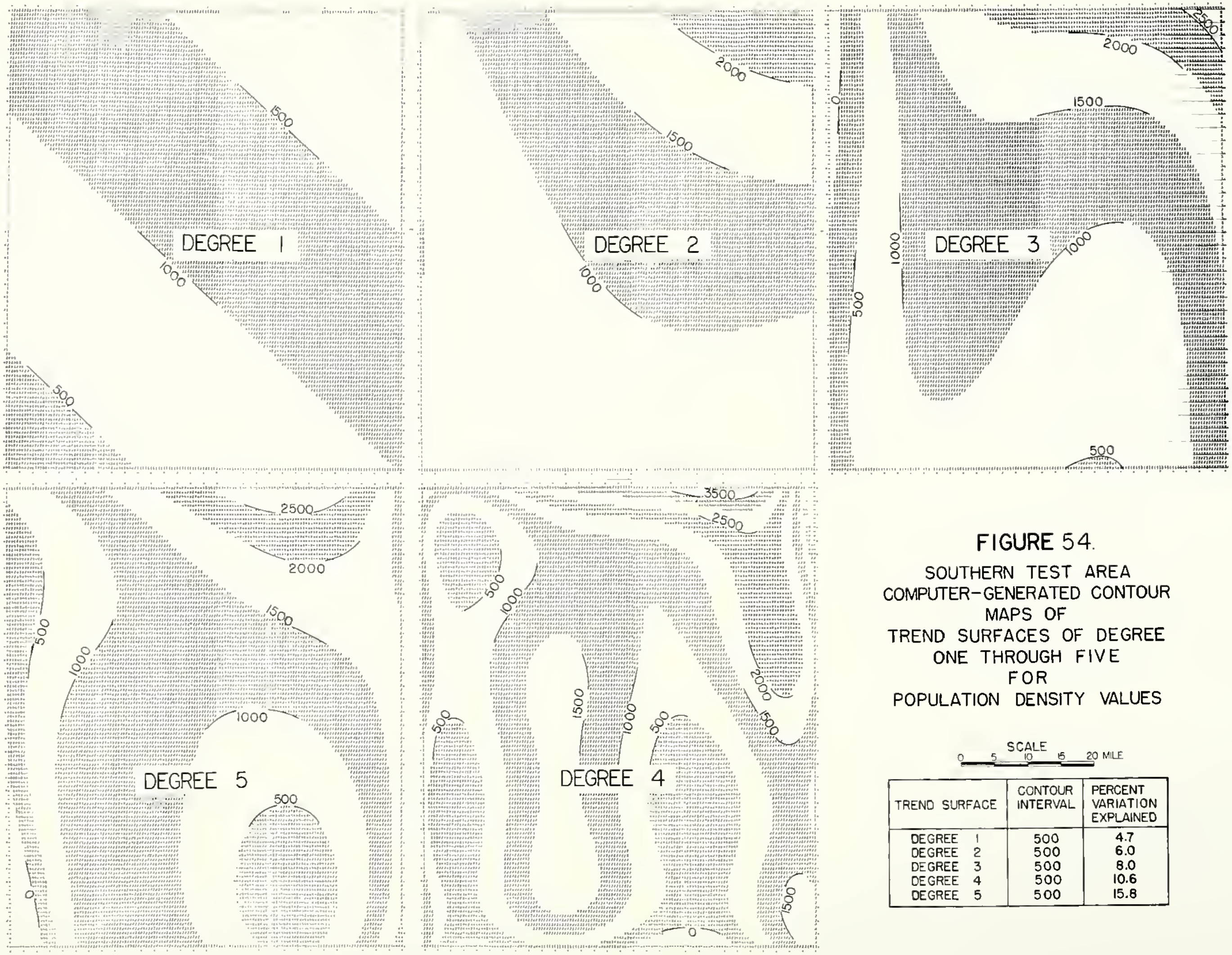


FIGURE 54.

SOUTHERN TEST AREA
COMPUTER-GENERATED CONTOUR
MAPS OF
TREND SURFACES OF DEGREE
ONE THROUGH FIVE
FOR
POPULATION DENSITY VALUES

TREND SURFACE	CONTOUR INTERVAL	PERCENT VARIATION EXPLAINED
DEGREE 1	500	4.7
DEGREE 2	500	6.0
DEGREE 3	500	8.0
DEGREE 4	500	10.6
DEGREE 5	500	15.8

Statistical testing of these surfaces was also undertaken. Table 8 (page 163) shows the results. Total and partial F-tests indicate these surfaces are relatively reliable in that their coefficients can be accepted as significantly different from zero with considerable confidence. The percent variation of the original data explained by these surfaces ranges from under five percent for the first degree surface up to 15.8 percent for the fifth degree surface.

The third measure used to study the service benefit factor was the quality of the existing road network. A rating scheme, shown in Table 10, was constructed so that the quality of the road network could be quantified at every intersection. The quantity at each intersection is the sum of the ratings of the roadways meeting at the intersection. Roadway intersections shown on the 1:250,000 scale topographic maps were digitized according to the procedures outlined for discrete measures in Chapter IV. Because an extremely large number of intersections are found within the southern test area a limiting criterion was established. Only intersections involving at least one "hard surface, medium-duty, two lane road," as defined on the 1:250,000 scale topographic map, were sampled. The resulting sample of 1054 road intersections described the major and secondary transportation systems, but ignored purely local distribution systems.

First through fifth degree surfaces were fitted to the data. Contour maps of these surfaces are shown in Figure 55. The first degree surface slopes downward from the southeast towards the northwest. The second degree surface forms a low in the northwest, and curves upward to higher values along the eastern edge and in the southwest corner. The

TABLE 10

SOUTHERN TEST AREA

ROADWAY RATINGS

Roadway Classification*	Rating
light duty two lane secondary	1.0
principal light duty two lane secondary	2.0
hard surface, medium duty, two lanes	4.0
hard surface, heavy duty, two lane state routes (except State Road 37)**	5.0
hard surface, heavy duty, two lane Federal routes and State Road 37**	6.0
hard surface, heavy duty, four lanes, (US 40 and US 31 in test area)	8.0

*Roads classified according to 1:250,000 scale topographic maps

**State Road 37 was given a higher rating since several sections are substantially above the quality of most state routes. It carries heavy traffic volumes to and from Bloomington.

3.0
4.0
DE(

2.0
4.0
6.0
4.0
DE
6.0
8.0

TABLE 10

SOUTHERN TEST AREA

ROADWAY RATINGS

Roadway Classification[*]	Rating
light duty two lane secondary	1.0
principal light duty two lane secondary	2.0
hard surface, medium duty, two lanes	4.0
hard surface, heavy duty, two lane state routes (except State Road 37)[**]	5.0
hard surface, heavy duty, two lane Federal routes and State Road 37[**]	6.0
hard surface, heavy duty, four lanes, (US 40 and US 31 in test area)	8.0

[*] Roads classified according to 1:250,000 scale topographic maps

[**] State Road 37 was given a higher rating since several sections are substantially above the quality of most state routes. It carries heavy traffic volumes to and from Bloomington.

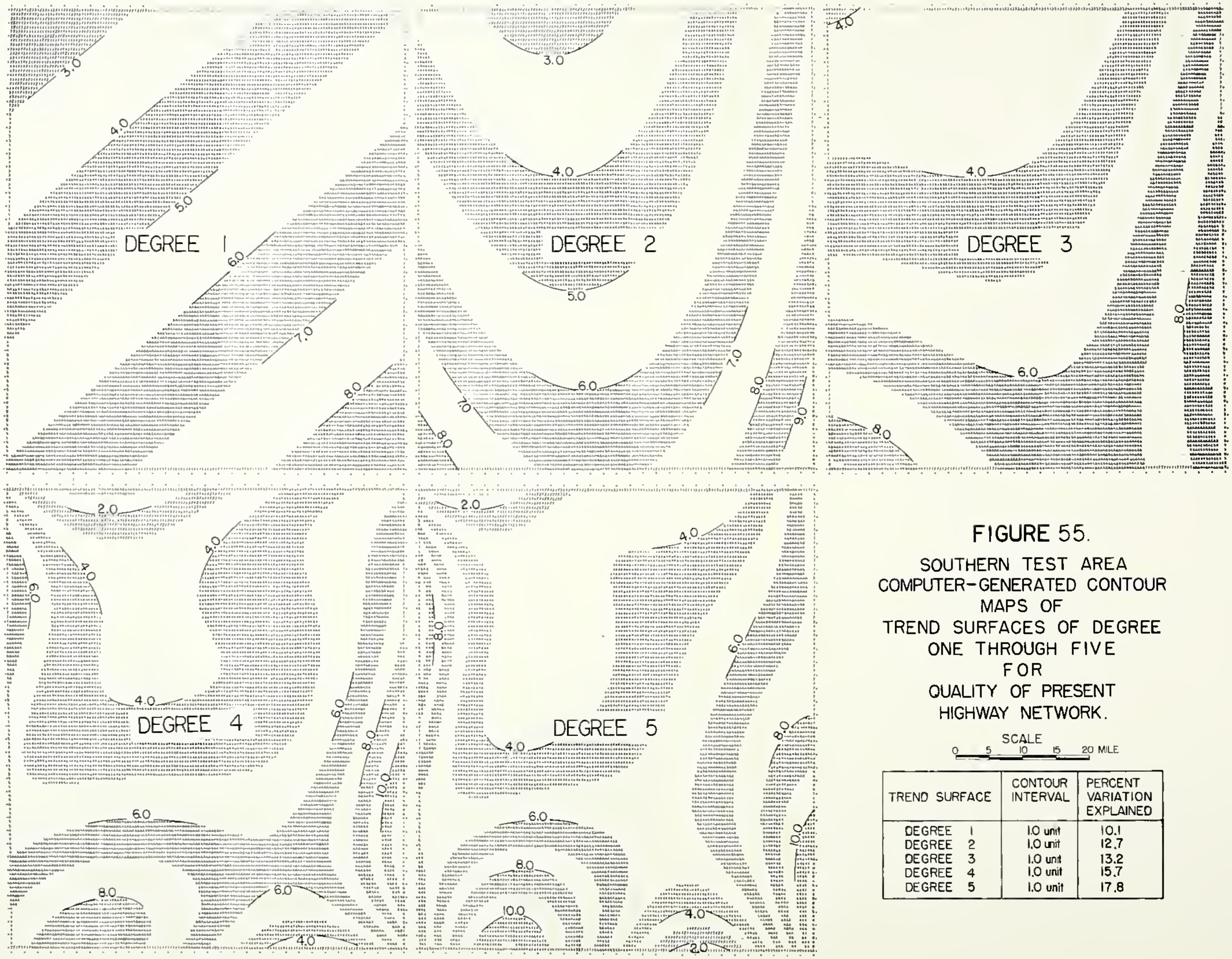


FIGURE 55.

SOUTHERN TEST AREA
COMPUTER-GENERATED CONTOUR
MAPS OF
TREND SURFACES OF DEGREE
ONE THROUGH FIVE
FOR
QUALITY OF PRESENT
HIGHWAY NETWORK.

TREND SURFACE	CONTOUR INTERVAL	PERCENT VARIATION EXPLAINED
DEGREE 1	1.0 unit	10.1
DEGREE 2	1.0 unit	12.7
DEGREE 3	1.0 unit	13.2
DEGREE 4	1.0 unit	15.7
DEGREE 5	1.0 unit	17.8

higher degree surfaces continue to show a low value region in the northwest and west central parts of the test area.

Total and partial F-tests indicate the coefficients of all surfaces can be accepted as significantly different from zero with high levels of confidence (see Table 8, page 163). The surfaces explain from slightly less than ten percent up to approximately 17.8 percent of the original data variability.

Comparison of the trend surfaces fitted to the three measures of the service benefit factor shows some similarities and some differences. Both sets of trend surfaces fitted to the two types of population data (see Figures 52 and 54) show high values in the northeast. Both first degree surfaces slope downward from the northeast. Higher degree surfaces show differences due to the data sources. The population density data appear to produce more realistic surfaces. In contrast, the road network quality data show a marked low along the State Road 37 corridor, an area of comparatively high population values. This apparent contradiction is in actual fact an accurate reflection of present conditions. Route 37 is greatly in need of improvement since it is the main transportation link between Bloomington and Indianapolis [120].

None of the trend surfaces explain a high percentage of the variations inherent in the original data sets. Accordingly the town populations, the population densities, and the road network qualities were estimated at a series of grid points by a weighted moving average procedure. These gridded values were used to form three alternative value surfaces of the service benefit factor. The population density value surface is shown as a contour map in Figure 53-B. The town populations

value surface and the road network quality value surface are shown in Figure 56.

Generation of Single Factor Alternatives

A suitable origin and destination must be selected before the generation of alternatives can begin. At the level of analysis being undertaken in the southern test area the generation of alternatives will be used to define Corridors.

The present and future transportation needs of the area have been studied [120]. As a result of these studies, it was decided to study two corridors; (1) a north-south corridor which runs through the area from south of Bedford to southwest of Indianapolis, and (2) an east-west corridor forming part of a new circumurban principal highway bypassing Indianapolis. A suitable origin and destination was selected for each corridor.

Results of Analysis for the North-South Corridor

Figures 57, 58 and 59 show the results obtained from the analysis of this corridor for selected single factors.

The earthwork costs factor was investigated using three different sets of residual values as previously described. Figures 57-A, 57-B, and 58-A show the generated alternatives for each set of residual values.

Analysis of the data derived from the 1:250,000 scale regional topographic maps results in generated alternatives (Figure 57-A) which follow eastern paths along the Scottsburg Lowland (see Figure 25, page 101). The fifth choice costs a little more than 134 percent of the first choice. Analysis of the second set of residuals yields a different combination

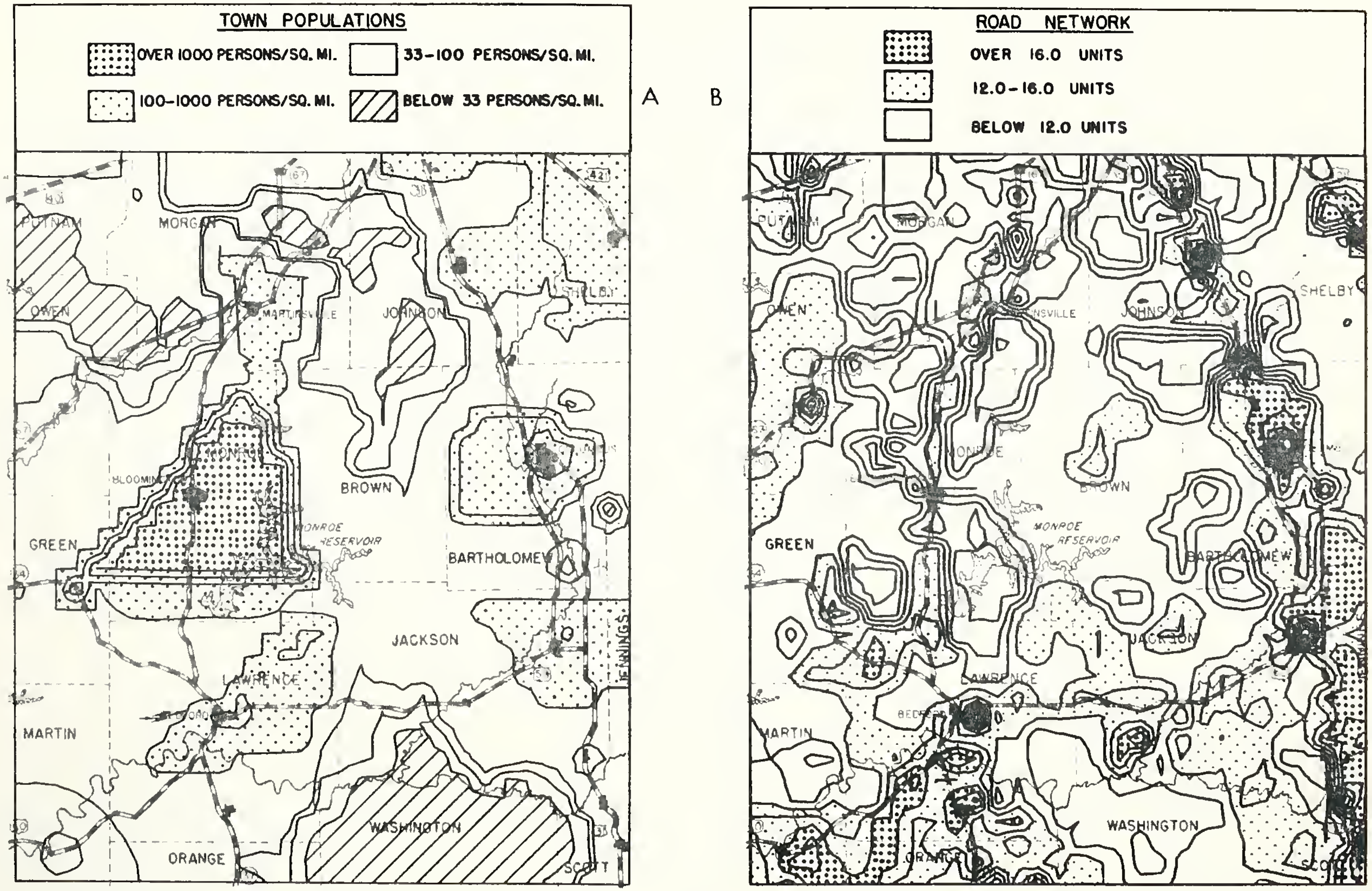
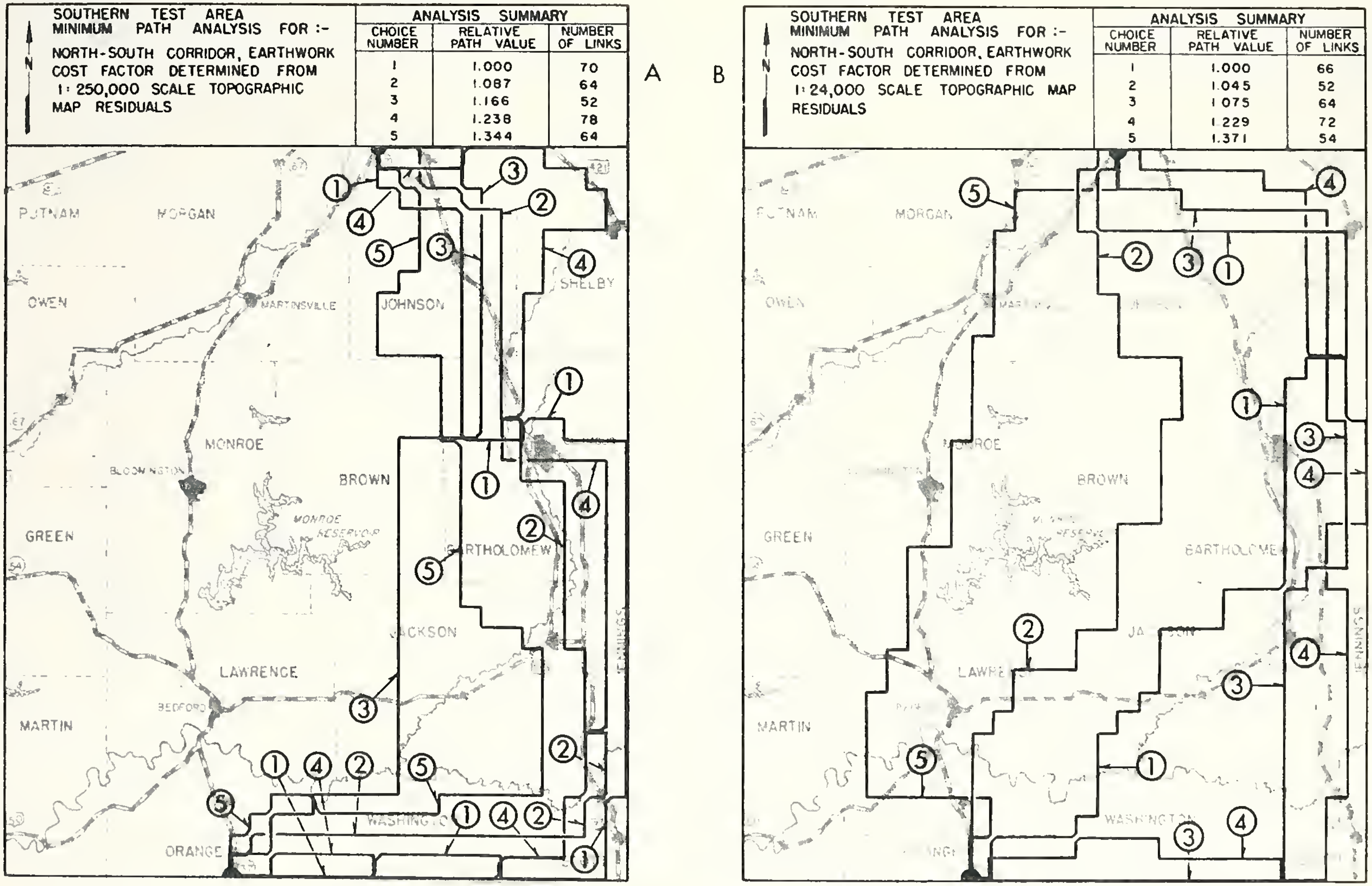


FIGURE 56. SOUTHERN TEST AREA - CONTOUR MAPS OF TOWN POPULATIONS AND ROAD NETWORK VALUE SURFACES.



A

SOUTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
NORTH-SOUTH CORRIDOR, EARTHWORK COST FACTOR DETERMINED FROM 1: 250,000 SCALE TOPOGRAPHIC MAP RESIDUALS

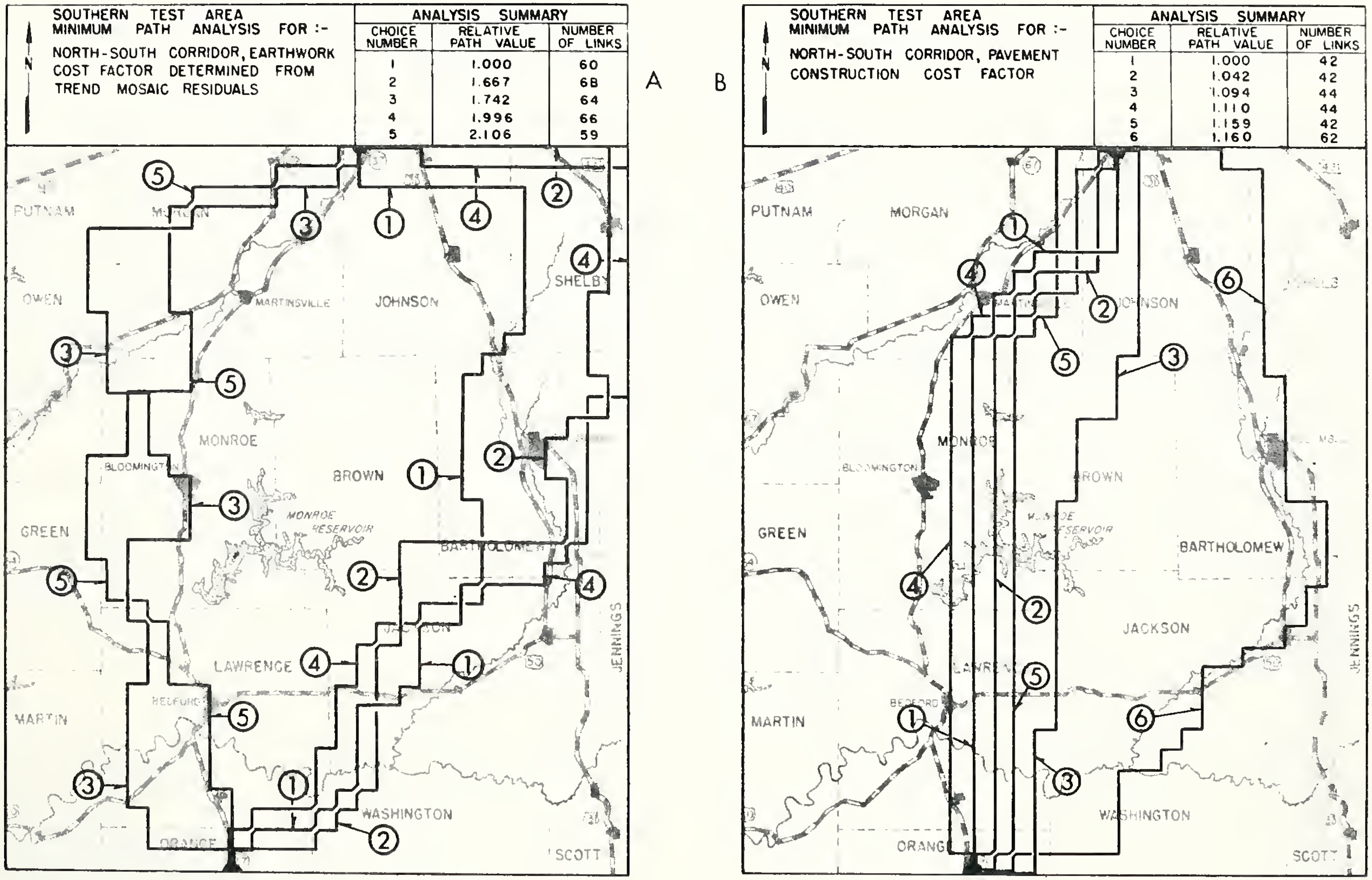
ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	70
2	1.087	64
3	1.166	52
4	1.238	78
5	1.344	64

B

SOUTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
NORTH-SOUTH CORRIDOR, EARTHWORK COST FACTOR DETERMINED FROM 1:24,000 SCALE TOPOGRAPHIC MAP RESIDUALS

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	66
2	1.045	52
3	1.075	64
4	1.229	72
5	1.371	54

FIGURE 57. SOUTHERN TEST AREA-GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.



A

SOUTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
NORTH-SOUTH CORRIDOR, EARTHWORK COST FACTOR DETERMINED FROM TREND MOSAIC RESIDUALS

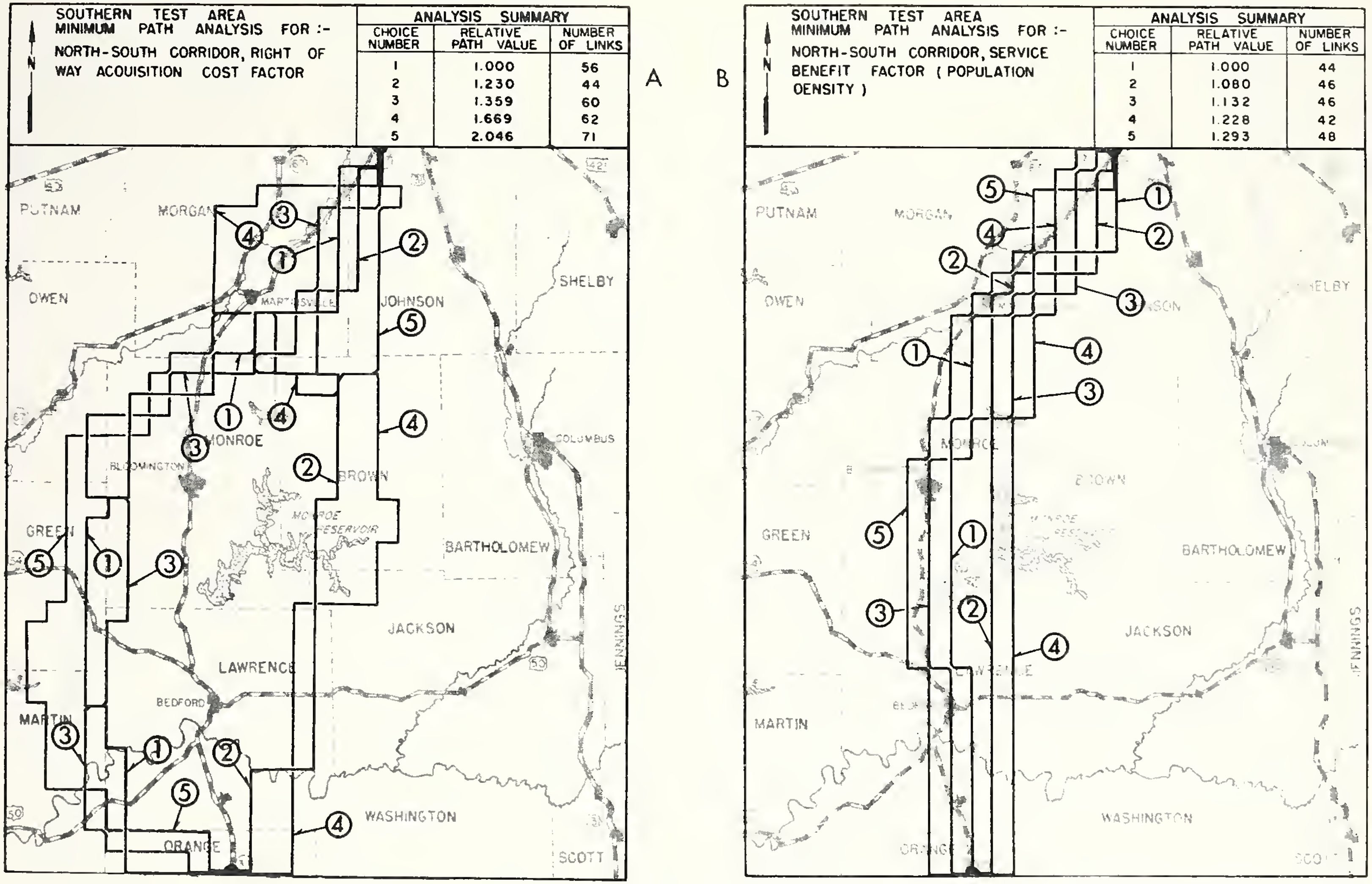
ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	60
2	1.667	68
3	1.742	64
4	1.996	66
5	2.106	59

B

SOUTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
NORTH-SOUTH CORRIDOR, PAVEMENT CONSTRUCTION COST FACTOR

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.042	42
3	1.094	44
4	1.110	44
5	1.159	42
6	1.160	62

FIGURE 58. SOUTHERN TEST AREA-GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.



A

SOUTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
NORTH-SOUTH CORRIDOR, RIGHT OF WAY ACOUISITION COST FACTOR

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	56
2	1.230	44
3	1.359	60
4	1.669	62
5	2.046	71

B

SOUTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
NORTH-SOUTH CORRIDOR, SERVICE BENEFIT FACTOR (POPULATION OENSITY)

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	44
2	1.080	46
3	1.132	46
4	1.228	42
5	1.293	48

FIGURE 59. SOUTHERN TEST AREA- GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.

of alternatives (Figure 57-B). While Scottsburg Lowland corridors are favored by choices one, three, and four, the second choice, which exceeds the first choice by less than five percent, favors a corridor along the eastern part of the Norman Upland, and the fifth choice closely parallels the present State Road 37 alignment along the Mitchell Plain and the valley of the West Fork White River past Martinsville.

As shown by Figure 58-A, the alternatives generated by analysis of the residuals to the mosaic trend surface define two alternative corridors. Choices one, two, and four favor an eastern path through the Scottsburg Lowland. Choices three and five follow the western part of the Mitchell Plain and then travel on the smoother topography of the Tipton Till Plain across the northwestern part of the test area to the destination. Thus it is obvious that from the standpoint of topography the Scottsburg Lowland forms an attractive route. This is shown by all three data sets. The larger scale (1:24,000) topographic maps gave results which are believed to be more realistic. However this is possibly due to the much larger sample size of 10,591 points, as opposed to only 900 points measured on the small scale topographic maps. The alternatives generated from the mosaic trend residual values are believed superior to the other sets of alternatives. Thus these residuals were used in the later multiple factor studies.

Figure 58-B shows those alternatives generated to minimize pavement construction costs. Choices one, two, four, and five parallel one another and follow the Mitchell Plain and the West Fork White River valley, essentially the present State Road 37 alignment. This location may be due partly to the presence of granular outwash materials along the West

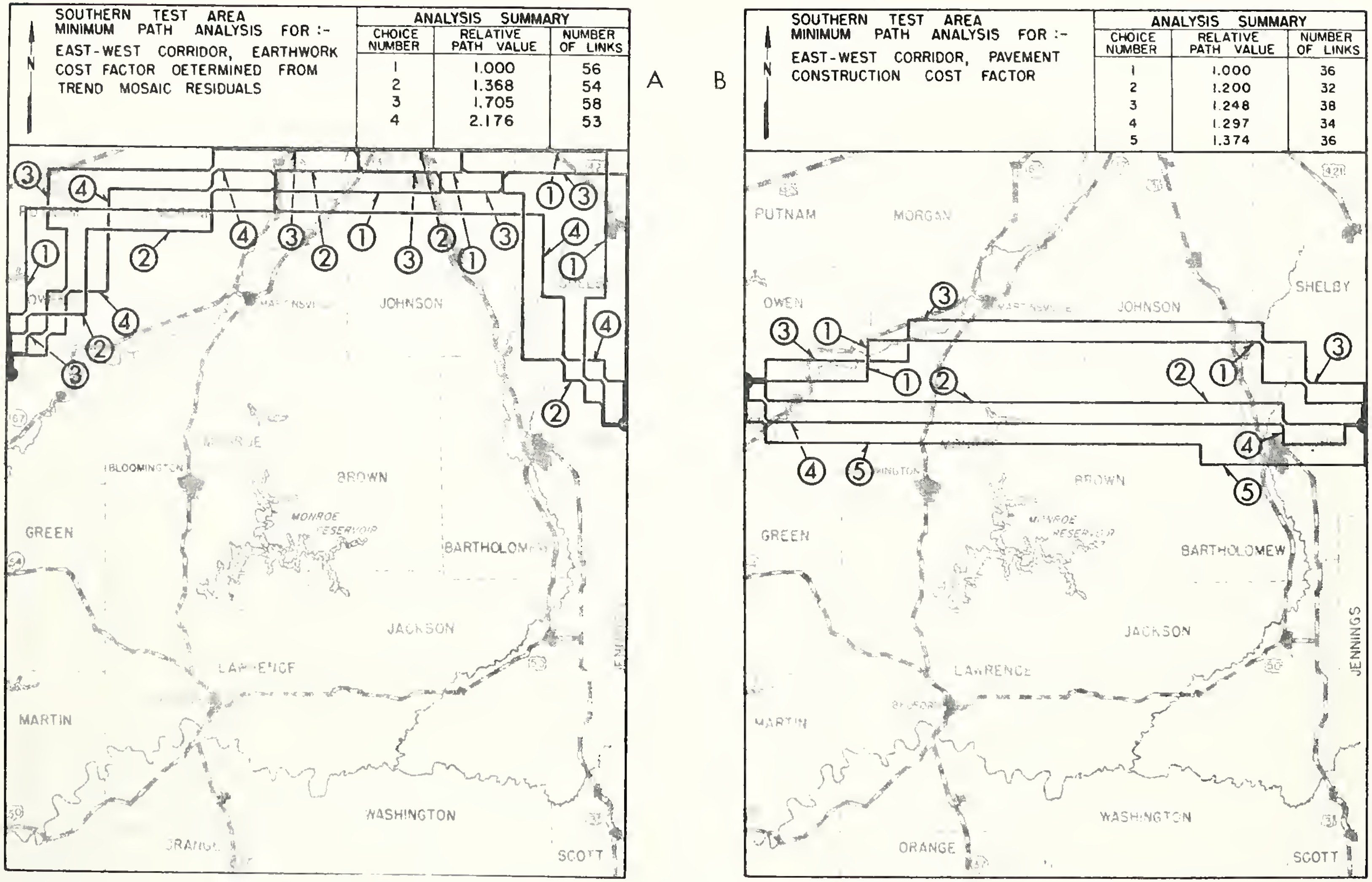
Fork White River. The fourth choice follows a more easterly path through central Brown County. Of considerably greater interest is the sixth choice which selects a corridor which follows the outwash deposits along the East Fork White River and thus travels along the Scottsburg Lowland. This sixth choice costs 16 percent more than the first choice.

Figure 59-A shows the generated alternatives which minimize the right of way acquisition costs. A marked preference for poor agricultural and forested land is evident. Two basic corridors are defined with choices one, three, and five favoring a western corridor mostly within the Crawford Upland and choices two and four favoring a central corridor within the Norman Upland. The two corridors merge south of Martinsville and all alternatives follow the southeast side of the West Fork White River valley except the fourth which crosses it and travels along its northwest side.

Figure 59-B shows the generated alternatives which maximize the service benefit factor, as measured by the population density data. The alternatives closely parallel each other and follow the present State Road 37 corridor, presently an area of considerable travel demand. These are typical of the results obtained for all measures of the service benefit factor studied for this area. The optimum is more clearly defined by the population density data than by the town populations only. Road network analysis shifts the alternatives slightly out of the actual corridor; however, the locations are not believed significantly different.

Results of Analysis for the East-West Corridor

The results of selected individual factor analyses for the east-west corridor are shown in Figures 60 and 61.



A

SOUTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
EAST-WEST CORRIDOR, EARTHWORK COST FACTOR DETERMINED FROM TREND MOSAIC RESIDUALS

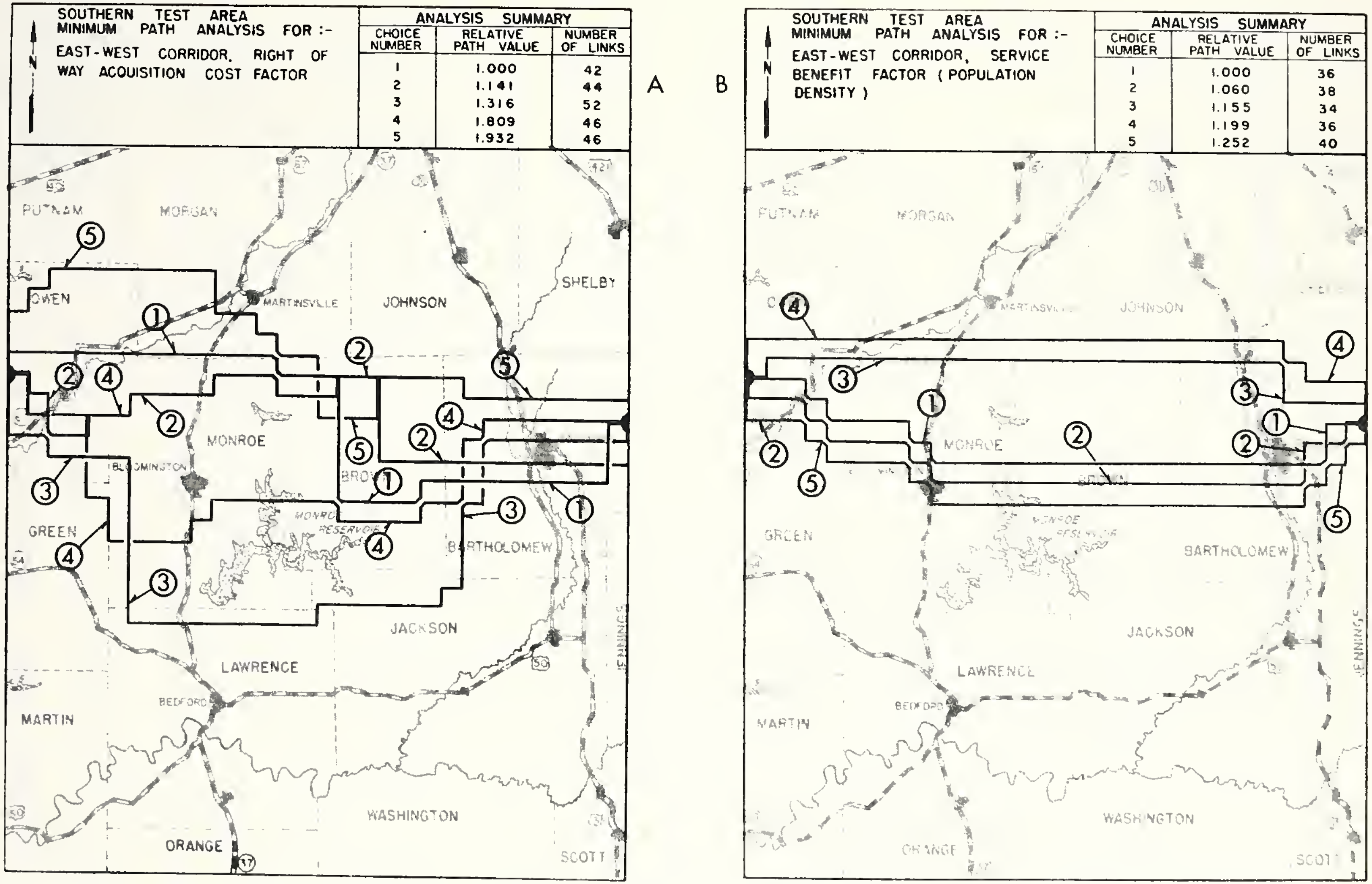
ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	56
2	1.368	54
3	1.705	58
4	2.176	53

B

SOUTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
EAST-WEST CORRIDOR, PAVEMENT CONSTRUCTION COST FACTOR

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	36
2	1.200	32
3	1.248	38
4	1.297	34
5	1.374	36

FIGURE 60. SOUTHERN TEST AREA - GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.



A

SOUTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
EAST-WEST CORRIDOR, RIGHT OF WAY ACQUISITION COST FACTOR

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.141	44
3	1.316	52
4	1.809	46
5	1.932	46

B

SOUTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
EAST-WEST CORRIDOR, SERVICE BENEFIT FACTOR (POPULATION DENSITY)

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	36
2	1.060	38
3	1.155	34
4	1.199	36
5	1.252	40

FIGURE 61. SOUTHERN TEST AREA - GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.

The alternatives generated to minimize the earthwork costs, as measured by the residuals to the mosaic trend surface, are shown in Figure 60-A. The results obtained from the other residual measures are essentially identical. The residuals to the mosaic trend surface gave the most sharply defined optimum, with the fourth choice cost exceeding twice the cost of the first choice. The alternatives define a single corridor which loops across the northern part of the test area, following the smooth glacial terrain of the Tipton Till Plain and avoiding the hilly terrain further to the south.

Figure 60-B shows the alternatives generated to minimize the pavement construction cost factor. Two parallel east-west corridors are defined. The first and third choices follow the West Fork White River for a short distance before striking due East, and so define a northern corridor. The other choices define a more southerly corridor.

The alternatives generated to minimize the right of way acquisition cost factor are shown in Figure 61-A. The first choice passes between Martinsville and Bloomington, then swings deeply into Brown County before passing south of Columbus to its destination. The second choice parallels the first choice on the south, crosses it, then parallels it on the north. The third and fourth choices follow more southerly routes. The third choice passes south of the Monroe Reservoir while the fourth choice travels closer to Bloomington and north of the reservoir. The fifth choice defines a more northerly corridor in the western part of the test area.

The various service benefit measures generate very similar alternatives. Figure 61-B shows the alternatives generated in response to the population density data. Two east-west corridors are generated; a southerly corridor defined by choices one, two, and five which passes close to Bloomington and Columbus, and a northerly corridor defined by choices three and four.

Generation of Multiple Factor Alternatives

A total of 24 multiple factor analyses* were analyzed in the southern test area. These were divided equally between the north-south and the east-west corridors. These analyses can be classified into three categories of varying complexities, as summarized in Table 11.

Two factor analyses are the simplest multiple factor studies; evaluation of the earthwork cost and the pavement construction cost factors allows the engineer to investigate route independent construction costs. The facility first costs can be more closely approximated by three factor analyses which include the earthwork cost, pavement construction cost, and right of way acquisition cost factors. The more complex four factor analyses include a measure of the service benefit factor which serves to temper the cost considerations.

Results of Analyses for the North-South Corridor

When the two factors of earthwork cost and pavement construction cost are combined equally the alternatives shown in Figure 62-A are generated. The first and fifth choices define a corridor which approximates the present State Road 37 alignment, while the remaining choices define a broad corridor lying to the east. However the choices are not greatly different in total cost; the fifth choice is less than eight percent greater than the first choice.

---

*The term "multiple factor analysis", as utilized in this thesis, bears no relationship to the statistical procedure of the same name.

TABLE 11

SOUTHERN TEST AREA

MULTIPLE FACTOR ANALYSES

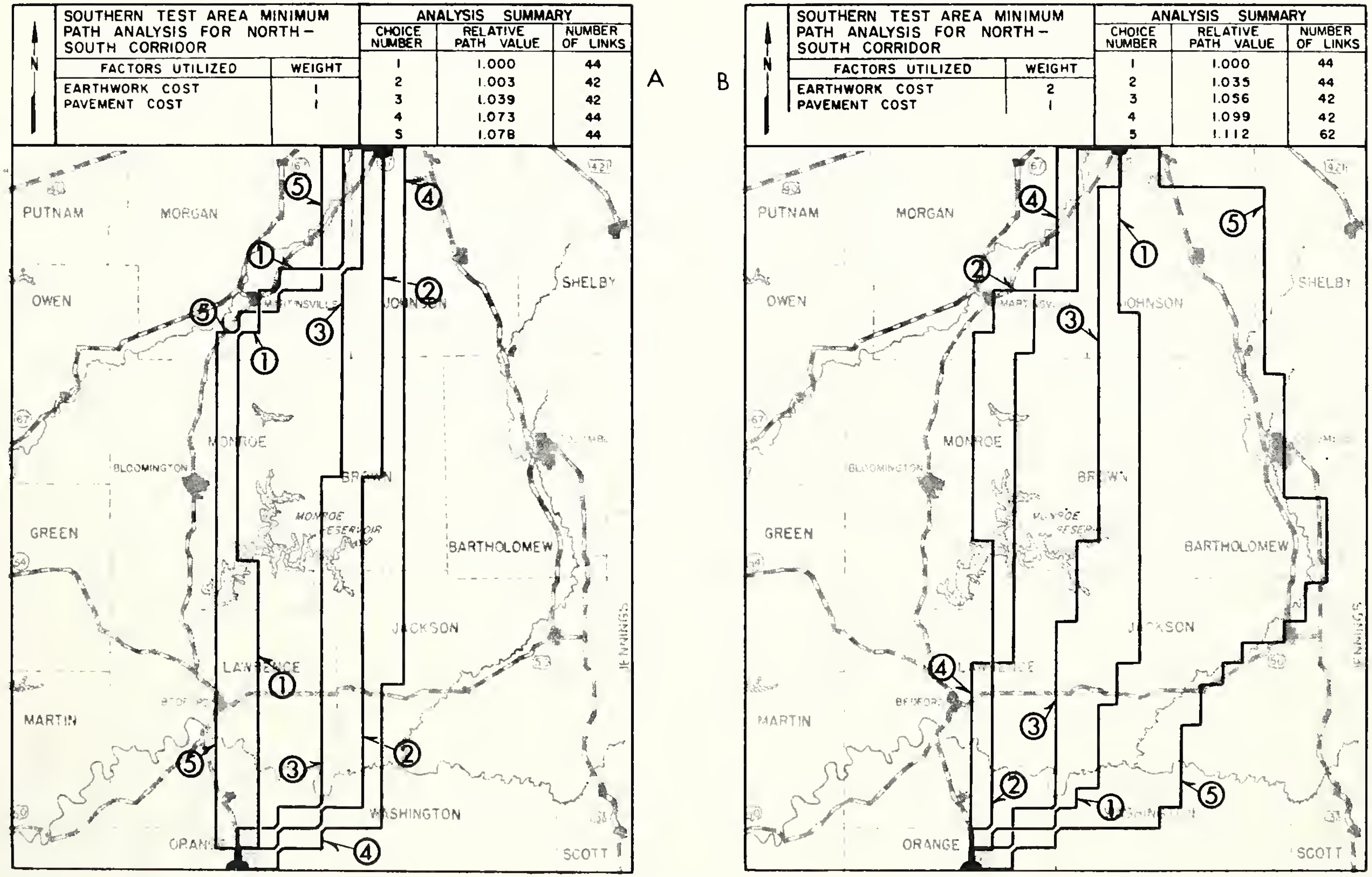
Category Of Analysis	Factor Weights Used in Each Analysis*			
	Earthwork Costs	Pavement Construction Costs	Right of Way Acquisition Costs	Population Density
Two Factor Analyses				
Trial (a)	1	1		
Trial (b)	1	2		
Trial (c)	2	1		
Three Factor Analyses				
Trial (d)	1	1	1	
Trial (e)	1	1	2	
Trial (f)	1	2	1	
Trial (g)	2	1	1	
Four Factor Analyses				
Trial (h)	1	1	1	1
Trial (i)	2	2	1	1
Trial (j)	1	1	2	1
Trial (k)	4	2	2	1
Trial (ℓ)	4	2	1	3

*Each analysis was performed twice; once for the North-South corridor and once for the East-West corridor.

Figure 62-B shows the alternatives generated when the earthwork cost is raised to predominance. The first and third choices define a corridor lying within the Norman Upland. The second and fourth choices define another corridor lying further to the west, while the fifth choice selects a corridor further to the east, up the Scottsburg Lowland. Although not shown, when the pavement construction cost factor is raised in importance similar corridors are generated. The relative importance of these corridors changes however. The first and fifth choices now define the western corridor while choices two and three define the Norman Upland corridor and the Scottsburg Lowland corridor is raised in importance, being defined by the fourth choice.

Figure 63-A shows the alternatives generated when the three factors of earthwork cost, pavement construction cost, and right of way acquisition cost are weighted equally. The first, second, and fourth choices define a corridor lying within the Norman Upland. The third choice closely approximates the present State Road 37 alignment while the fifth choice defines a corridor between the first and third choices.

The alternatives generated when the right of way acquisition cost factor is raised in importance are shown in Figure 63-B. The corridors are defined by the five alternatives. The first, second, and fifth choices define a corridor running through the low cost land in the Norman Upland. Choices three and four lie further to the west. The generated alternatives indicate the interactions between right of way costs and construction costs. Cheap land is found in areas of rough terrain, while smooth areas are areas of high land cost. A reduction in construction costs allows a corridor to follow more expensive land in the Mitchell Plain, as



A

SOUTHERN TEST AREA MINIMUM PATH ANALYSIS FOR NORTH-SOUTH CORRIDOR

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	44
2	1.003	42
3	1.039	42
4	1.073	44
5	1.078	44

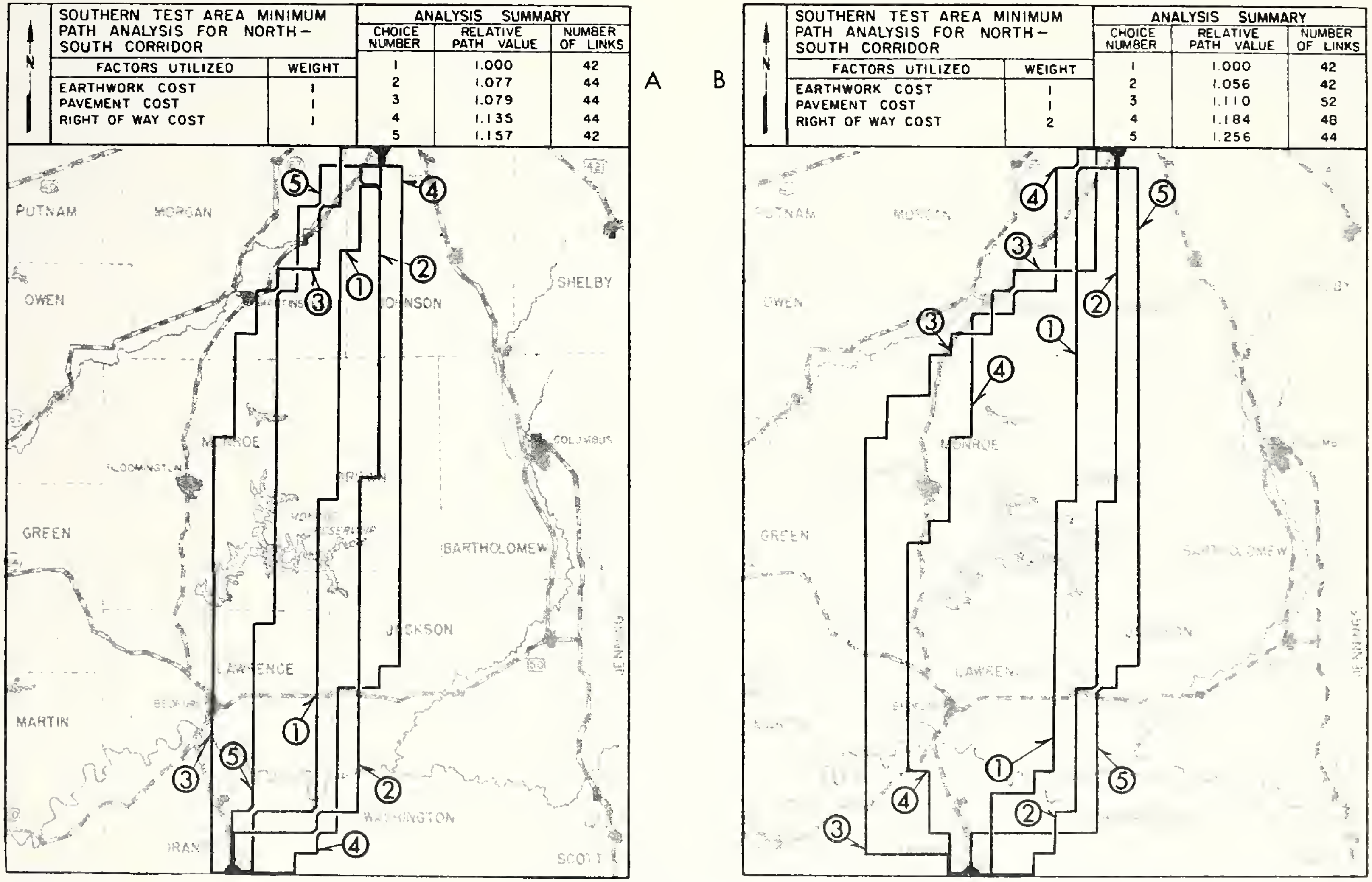
B

SOUTHERN TEST AREA MINIMUM PATH ANALYSIS FOR NORTH-SOUTH CORRIDOR

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	2
PAVEMENT COST	1

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	44
2	1.035	44
3	1.056	42
4	1.099	42
5	1.112	62

FIGURE 62. SOUTHERN TEST AREA-GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.



A

SOUTHERN TEST AREA MINIMUM PATH ANALYSIS FOR NORTH-SOUTH CORRIDOR

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.077	44
3	1.079	44
4	1.135	44
5	1.157	42

B

SOUTHERN TEST AREA MINIMUM PATH ANALYSIS FOR NORTH-SOUTH CORRIDOR

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	2

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.056	42
3	1.110	52
4	1.184	48
5	1.256	44

FIGURE 63. SOUTHERN TEST AREA-GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.

shown by the fourth choice in Figure 63-B.

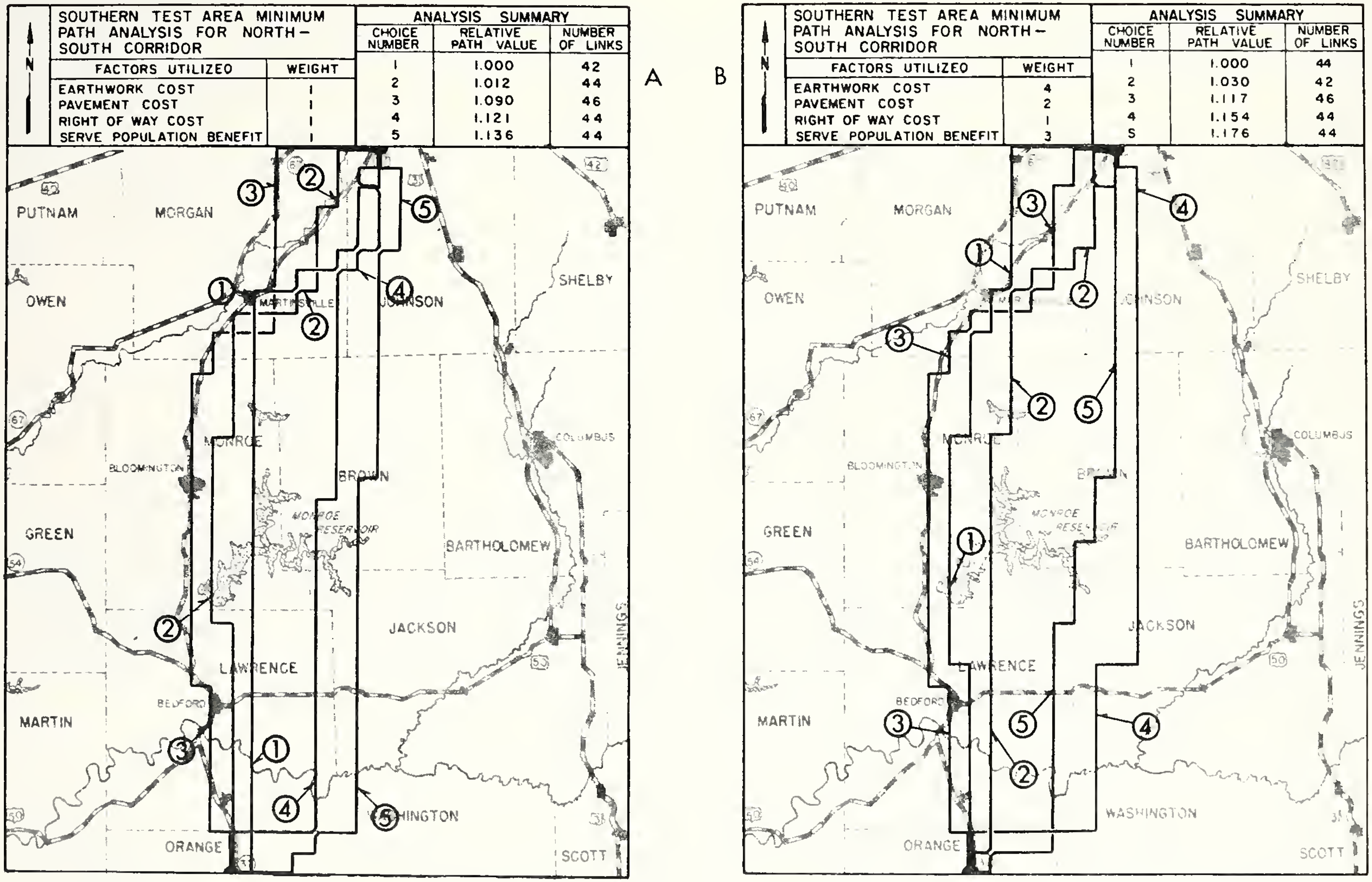
When four factors, including one measure of the service benefit factor, are studied, the alternatives shown in Figure 64 are generated. Figure 64-A shows the alternatives generated when the four factors are given equal weights. The first, second, and third choices approximately follow the present State Road 37 alignment. However the first choice lies slightly to the east, avoiding both the most expensive land and the worst of the topographic conditions. The fourth and fifth choices define an alternative easterly corridor, within the Norman Upland. All generated alternatives are close to each other in total costs, the fifth choice costs less than 14 percent more than the first choice.

Although not shown, raising the importance of the right of way cost factor favors easterly corridors within the Norman Upland, and raising either or both of the earthwork cost or pavement construction cost factors tends to favor more westerly corridors.

Figure 64-B shows the alternatives generated for what is probably a realistic weighting of the various factors: earthwork cost (40%); pavement construction cost (20%); right of way acquisition cost (10%); and the service benefit factor measured by the population density (30%). Now choices one, two, and three define a corridor along the present State Road 37, although the second choice lies somewhat to the east. The fourth and fifth choices lie farther to the east, within the Norman Upland. These choices reflect the interactions between the costs and the benefits.

Results of Analyses for the East-West Corridor

Figure 65-A shows a typical set of alternatives generated in response to the two factors of earthwork cost and pavement construction cost. A



A

SOUTHERN TEST AREA MINIMUM PATH ANALYSIS FOR NORTH-SOUTH CORRIDOR

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1
SERVE POPULATION BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.012	44
3	1.090	46
4	1.121	44
5	1.136	44

B

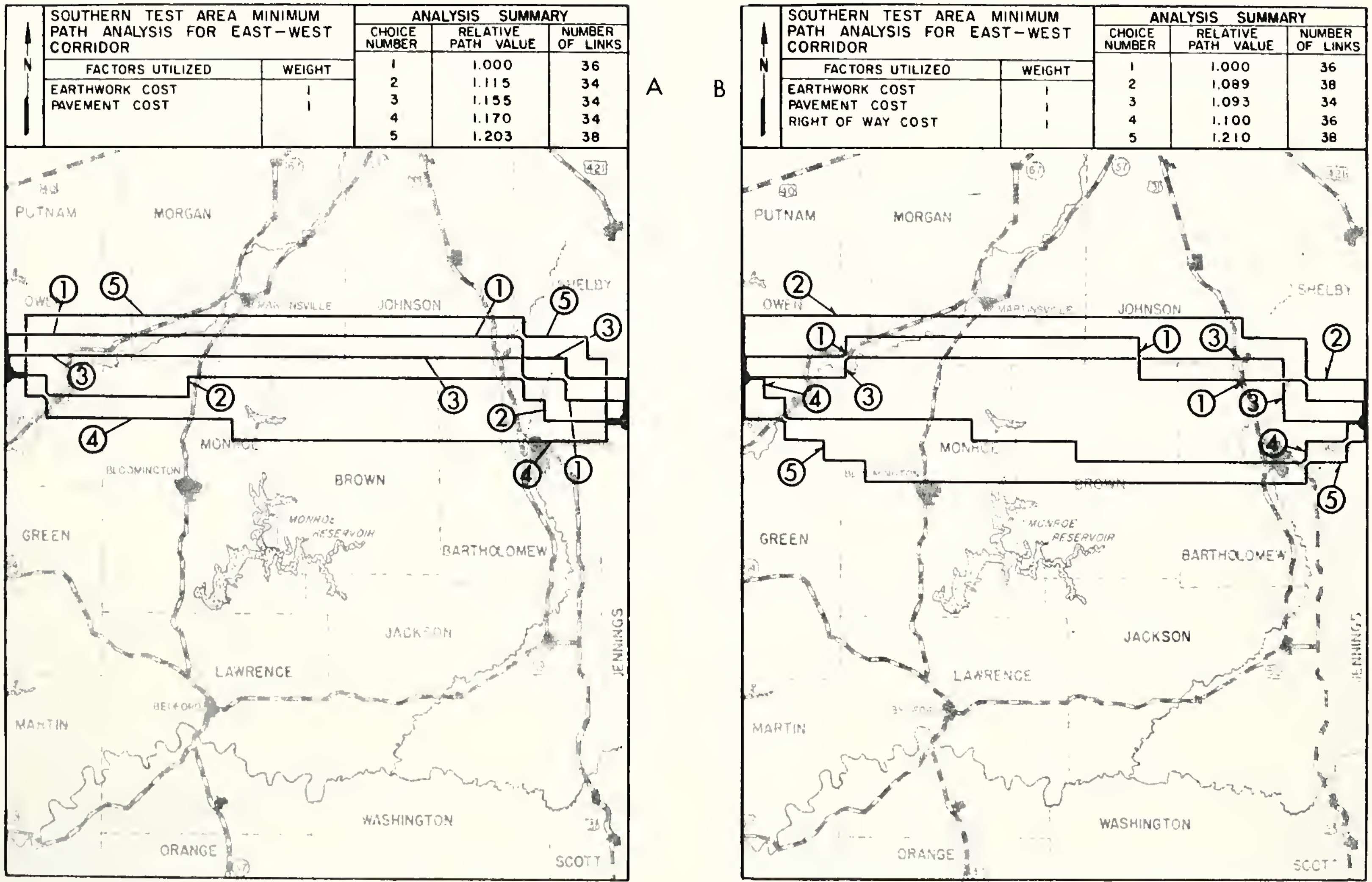
SOUTHERN TEST AREA MINIMUM PATH ANALYSIS FOR NORTH-SOUTH CORRIDOR

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	4
PAVEMENT COST	2
RIGHT OF WAY COST	1
SERVE POPULATION BENEFIT	3

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	44
2	1.030	42
3	1.117	46
4	1.154	44
5	1.176	44

FIGURE 64. SOUTHERN TEST AREA-GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.



A

SOUTHERN TEST AREA MINIMUM PATH ANALYSIS FOR EAST-WEST CORRIDOR

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	36
2	1.115	34
3	1.155	34
4	1.170	34
5	1.203	38

B

SOUTHERN TEST AREA MINIMUM PATH ANALYSIS FOR EAST-WEST CORRIDOR

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1

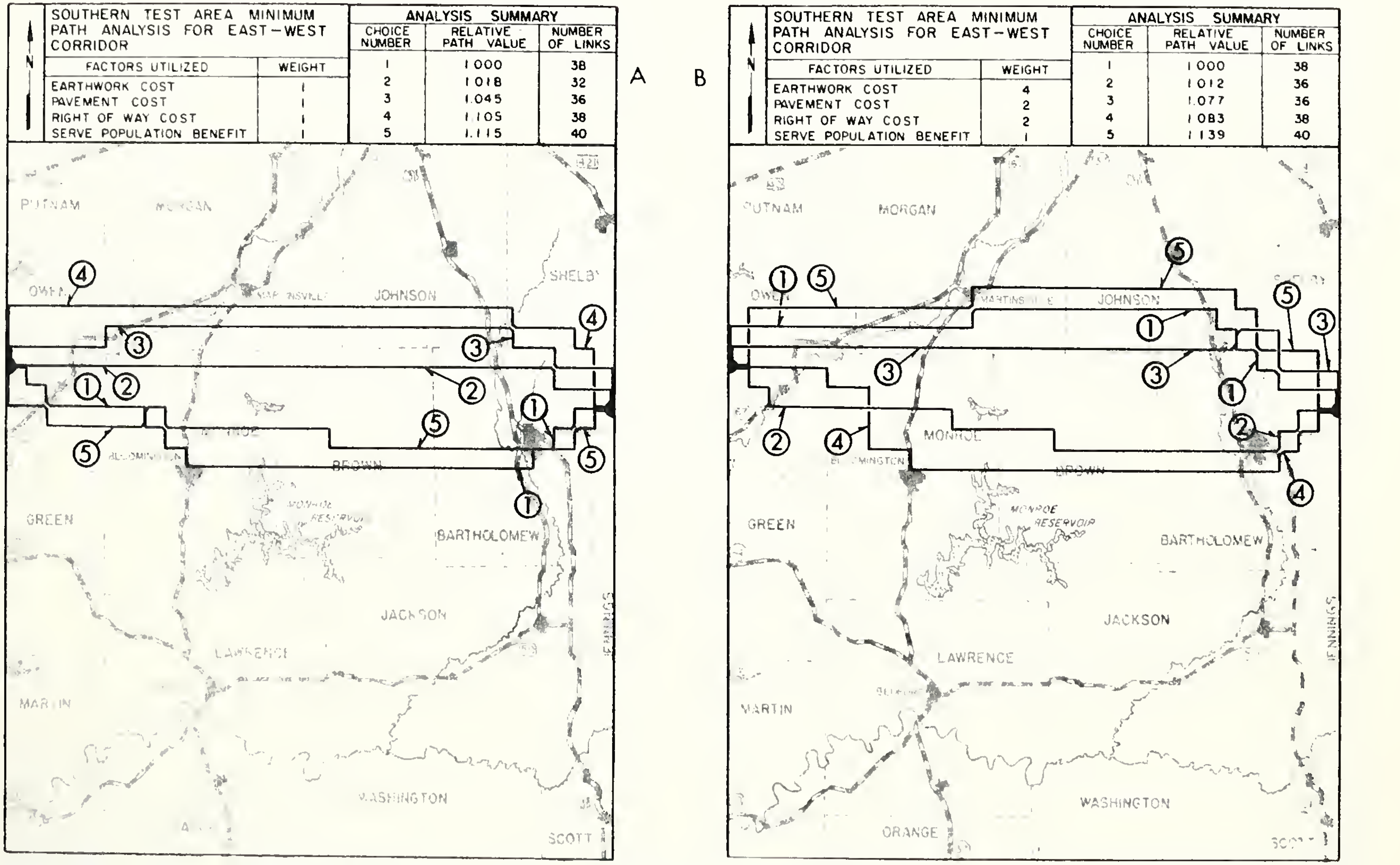
ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	36
2	1.089	38
3	1.093	34
4	1.100	36
5	1.210	38

FIGURE 65. SOUTHERN TEST AREA-GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.

single east-west corridor is defined, although the fourth choice can be considered to define a significantly different more southerly path. The alternatives shown were generated with the factors having equal weights; however little change occurs if the importance of either factor is increased.

Figure 65-B shows typical results of a three factor analysis. Two east-west corridors are evident; a northerly corridor defined by alternatives one, two, and three, and a southerly one defined by the fourth and fifth alternatives. Although not shown, increasing the importance of the pavement construction cost causes the alternatives to resemble the two-factor alternatives shown in Figure 65-A; while increasing the importance of the right of way acquisition cost factor raises the attractiveness of the southerly corridor.

Adding a fourth factor to the analysis to measure the service benefit factor results in the generation of the alternatives shown in Figure 66. When the four factors are given equal weights the southerly corridor is given added importance, as shown in Figure 66-A, being defined by the first choice. The southern corridor passes close to Bloomington and Columbus, while the northern corridor passes close to Martinsville and Edinburg. Figure 66-B shows the alternatives generated when the four factors are weighted in what is believed to be a realistic manner: earthwork cost (45%); pavement construction cost (22%); right of way acquisition cost (22%); and the service benefit factor measured by population density (11%). Under these conditions, the first, third, and fifth choices define a northern corridor; the second and fourth choices, a southern corridor. There is little spread in the costs of the alternatives



A

SOUTHERN TEST AREA MINIMUM PATH ANALYSIS FOR EAST-WEST CORRIDOR

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1
SERVE POPULATION BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	38
2	1.018	32
3	1.045	36
4	1.105	38
5	1.115	40

B

SOUTHERN TEST AREA MINIMUM PATH ANALYSIS FOR EAST-WEST CORRIDOR

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	4
PAVEMENT COST	2
RIGHT OF WAY COST	2
SERVE POPULATION BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	38
2	1.012	36
3	1.077	36
4	1.083	38
5	1.139	40

FIGURE 66. SOUTHERN TEST AREA-GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.

however, since the fifth choice costs less than 14 percent more than the first choice.

Evaluation of Alternatives

The final analyses of the north-south and east-west corridors are shown in Figures 64-B and 66-B. However the alternatives shown were generated in response to purely route-independent factors. These alternatives should therefore be re-evaluated to determine if they should be re-ordered to reflect the route-dependent factors.

Shorter routes generally will have lower user costs and higher user benefits associated with them because, at the same level of service, travel time will be less as will all length dependent costs such as vehicle operating costs, and facility maintenance. The importance of such costs relative to the first costs of construction must be decided on by the engineer. Under high traffic volumes the importance of such factors may equal or exceed first costs. If the route-dependent costs are assumed to equal the first costs, alternatives already generated should be re-ordered if any lower numbered choice in the sequence, when compared to a higher numbered choice, shows a percent reduction in length which is greater than the percent increase in first costs.

When this criterion is applied to the alternatives for the north-south corridor shown in Figure 64-B, some re-ordering is shown to be desirable. The second choice costs only three percent more than the first choice, yet it is 4.5 percent shorter (42 links to 44 links). On the other hand although the third choice costs about three percent less than the fourth choice, it is five percent longer (46 links to 44 links). Thus the alternatives should be re-ordered as follows:- (1) choice two,

(2) choice one, (3) choice four, (4) choice three, and (5) choice five. This re-ordering improves the relative position of the corridor located within the Norman Upland.

When the same criterion is applied the east-west corridor alternatives shown in Figure 66-B only the first and second alternatives change places. However this does serve to increase the attractiveness of the southern corridor.

It must be noted that a different ordering will probably result if different relative importance is attached to the two classes of highway location factors.

CHAPTER VI

ANALYSIS OF NORTHERN TEST AREA

Investigation of Route Independent Highway Location Factors

The pertinent characteristics of the northern test area are described in Chapter IV and are summarized in Figures 28, 29, 30, 31, and 32 (see pages 108, 110, 111, 112, and 114).

Seven measures were used to evaluate the four route-independent factors of earthwork cost, pavement construction cost, right of way acquisition cost, and service benefits. The measures were prepared in graphical form as maps at suitable scales. These were sampled to produce numerical measures which were converted first to values and later to utilities. Table 4 (page 115) summarizes the measures, values, utilities and associated transformation procedures for each factor.

Trend surface analysis was used to check the values for accuracy and for lack of bias. Once this was established, transformation of the values to utilities was undertaken, followed by generation of single factor alternatives. Generation of multiple factor alternatives and re-ordering of these alternatives to reflect route dependent factors completed the analysis.

The analysis shows the utility of the GCARS System for studying new bypass alternatives near medium sized urban areas. The studies are considered to be representative of the Corridor or Route levels of the highway planning hierarchy.

Derivation of a Value Surface for the Earthwork Cost Factor

The general topographic conditions of the northern test area are shown in Figure 28 (page 108). Spot elevations were measured from standard 1:24,000 topographic quadrangles having ten foot contour intervals. As shown in Figure 67, portions of six quadrangles cover the test area. Each map was digitized separately; the X and Y coordinates being measured from an arbitrary origin at the lower left hand corner of each map. Once all the maps were digitized, the data was processed to convert the coordinates to latitude and longitude values. Minor map scale changes and rotations were corrected. The data was stored on magnetic tape. A total of 2521 spot elevations were distributed throughout the area.

First through fifth degree trend surfaces were fitted to these elevation values. The computer-generated contour maps in Figure 68 shows the shapes of these surfaces. Statistical measures were obtained for these surfaces and are shown in Table 12. The following statements are based on the statistical analysis and on a careful examination of the contour maps of these trend surfaces.

The first degree surface forms a plane dipping gently toward the northeast. It explains less than five percent of the variability of the original elevation data. However the total and partial F tests show its coefficients to be highly significant. In other words it shows a true regional dip. This tendency to lower elevations in the northeast probably reflects the greater width of the Wabash valley northeast of Lafayette, and the presence of low elevation values along Wildcat Creek in the

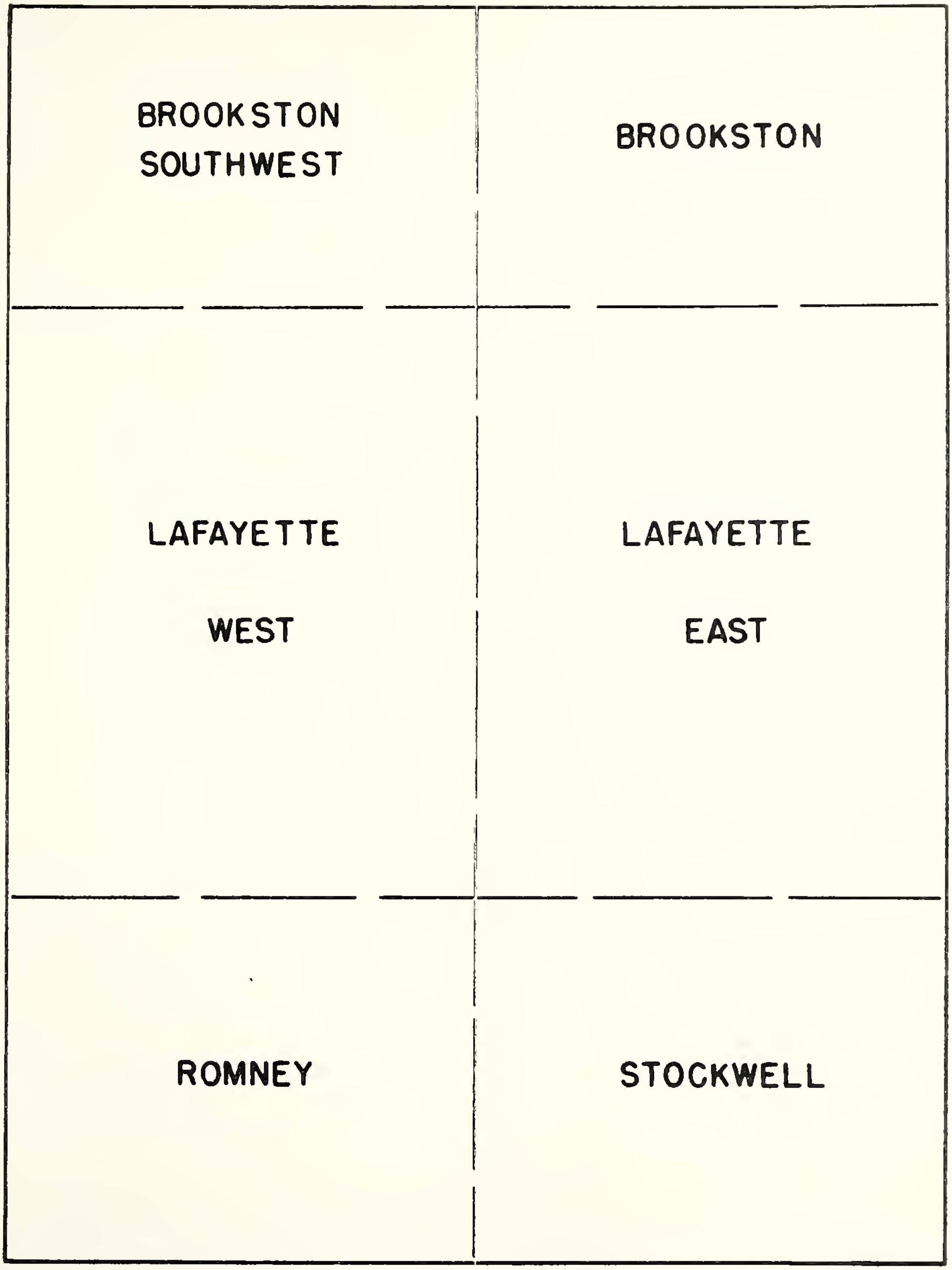
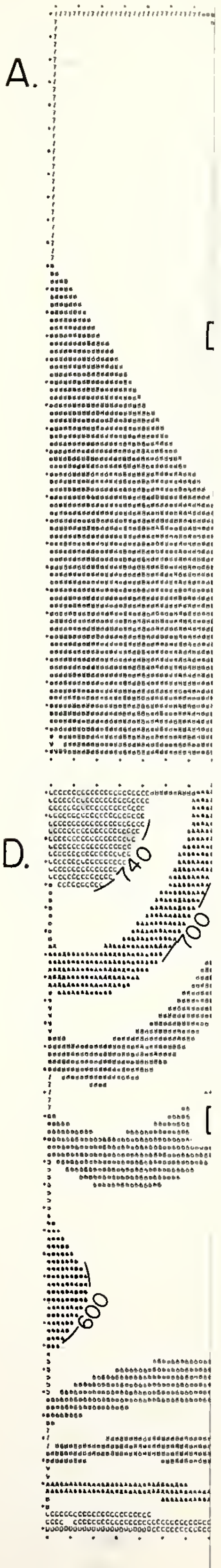


FIGURE 67. THE SIX TOPOGRAPHIC MAPS COVERING THE NORTHERN TEST AREA.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D.
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700
600

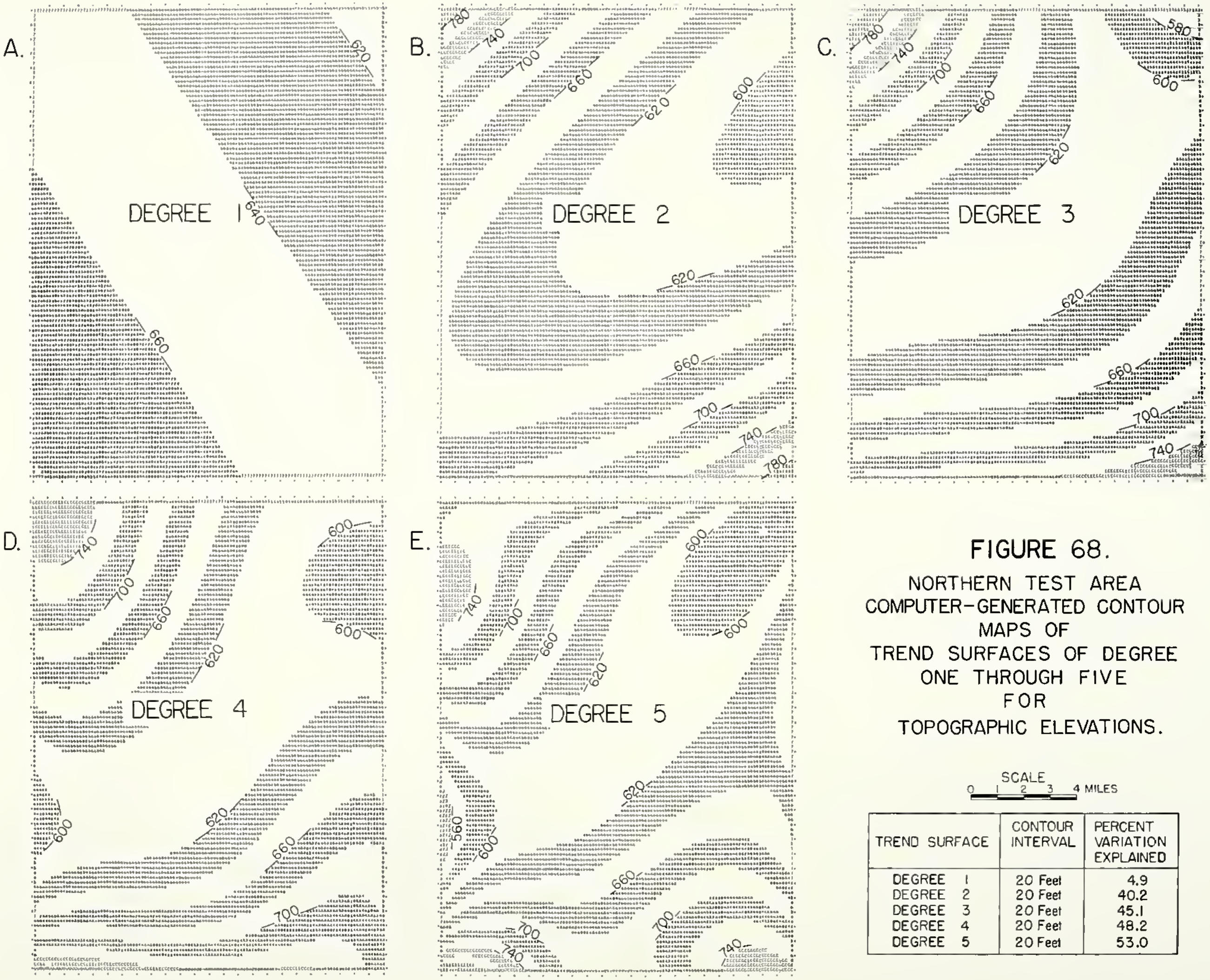


FIGURE 68.

NORTHERN TEST AREA
COMPUTER-GENERATED CONTOUR
MAPS OF
TREND SURFACES OF DEGREE
ONE THROUGH FIVE
FOR
TOPOGRAPHIC ELEVATIONS.

SCALE
0 1 2 3 4 MILES

TREND SURFACE	CONTOUR INTERVAL	PERCENT VARIATION EXPLAINED
DEGREE 1	20 Feet	4.9
DEGREE 2	20 Feet	40.2
DEGREE 3	20 Feet	45.1
DEGREE 4	20 Feet	48.2
DEGREE 5	20 Feet	53.0

TABLE 12

NORTHERN TEST AREA - RESULTS OF STATISTICAL ANALYSES - I

Values or Measures	Degree of Trend Surface	Analysis of Variance						
			Total F-Tests			Partial F-Tests of Highest Degree Trend		
		Percent Variation Explained	Degrees of Freedom	Computed F-Value	Level of Significance (1-α)	Degrees of Freedom	Computed F-Value	Level of Significance (1-α)
Elevations from 1:24,000 Scale Topographic Maps	1	4.9	3,2517	43.6	.99	2,2518	131.3	.99
	2	40.2	6,2514	281.5	.99	3,2517	625.0	.99
	3	45.1	10,2510	206.6	.99	4,2516	65.9	.99
	4	48.2	15,2505	155.5	.99	5,2515	32.6	.99
	5	53.0	21,2499	134.3	.99	6,2514	42.6	.99
Pavement Construction Cost	1	1.1	3,605	2.3	.90	2,606	3.7	.975
	2	4.7	6,602	5.0	.99	3,605	7.9	.99
	3	6.0	10,598	3.8	.99	4,604	2.1	.90
	4	7.8	15,593	3.3	.99	5,603	2.4	.95
	5	11.0	21,587	3.5	.99	6,602	3.6	.99
Right of Way Acquisition Cost	1	1.8	3,209	1.3	.50	2,210	2.5	.90
	2	22.1	6,206	9.7	.99	3,209	18.6	.99
	3	24.9	10,202	6.7	.99	4,208	1.9	.90
	4	29.7	15,197	5.6	.99	5,207	2.7	.975
	5	30.6	21,191	4.0	.99	6,206	0.4	.10

eastern part of the map area (see Figure 28, page 108).

The second degree trend surface forms a syncline plunging to the northeast. The map area is thus divided into a high area in the northwest, and another high in the southeast and south; there being separated by an intervening low one. Comparison of this surface with Figure 28 (page 108) shows that the presence of the Wabash Valley is now being made more evident. Study of the statistics in Table 12 shows that the percent variation explained has jumped to just over forty percent, while the partial and total F-tests leave no doubt as to the significance of these coefficients.

The third degree trend surface shows the curve of the Wabash Valley. The statistics show an increase of about five percent in the percent variation explained by this surface over the second degree. The coefficients remain significant.

The fourth and fifth degree trend surfaces continue to add refinements to this basic pattern. The fourth degree surface begins to show some response to the presence of Wildcat Creek along the eastern border. The fifth degree surface carries this effect further and adds a low in the south central part of the map area which reflects the presence of Wea Creek. A widening of the low zone in the western part of the map may possibly reflect the presence of Indian Creek. These surfaces retain a high significance in their coefficients and add a few percentage points to the percent variation explained.

Of all the surfaces, the fifth degree surface expresses the regional topography in the most satisfactory manner. Over 53 percent of the variability in the original elevation values is explained by this surface.

Accordingly, a piece-wise analysis and construction of a trend mosaic surface, as performed in the southern test area, was believed unnecessary. The fifth degree trend surface was selected as the best smoothed grade-line surface. A weighted moving average procedure was applied to the residuals to this surface. The resulting interpolated grid values were utilized to form the value surface for the earthwork cost factor. Figure 69 shows a computer generated map of the residuals based on these interpolated values.

Derivation of a Value Surface for the Pavement Construction Cost Factor

Information on the distribution of soil types for the northern test area was obtained from the Tippecanoe County Engineering Soils Map prepared by Yeh [133]. Figure 29 (page 110) shows the portion of the map covering the test area.

Ten soil types are mapped within the test area. Each was given a code number and the map was digitized according to the procedures outlined for homogeneous discontinuous measures in Chapter IV. A total of 609 sample points was required.

The code numbers representing the engineering soil types are a measure. Conversion of this measure to a value for the pavement construction cost factor was accomplished by the use of the soil ratings developed by Ulbricht [118]. The procedure was identical to that utilized in the southern test area and described previously. Table 13 gives the values utilized. Two engineering soil units, ground moraine and ground moraine covered with thin loess, were judged essentially identical in pavement construction costs in this area and thus were given identical weights.

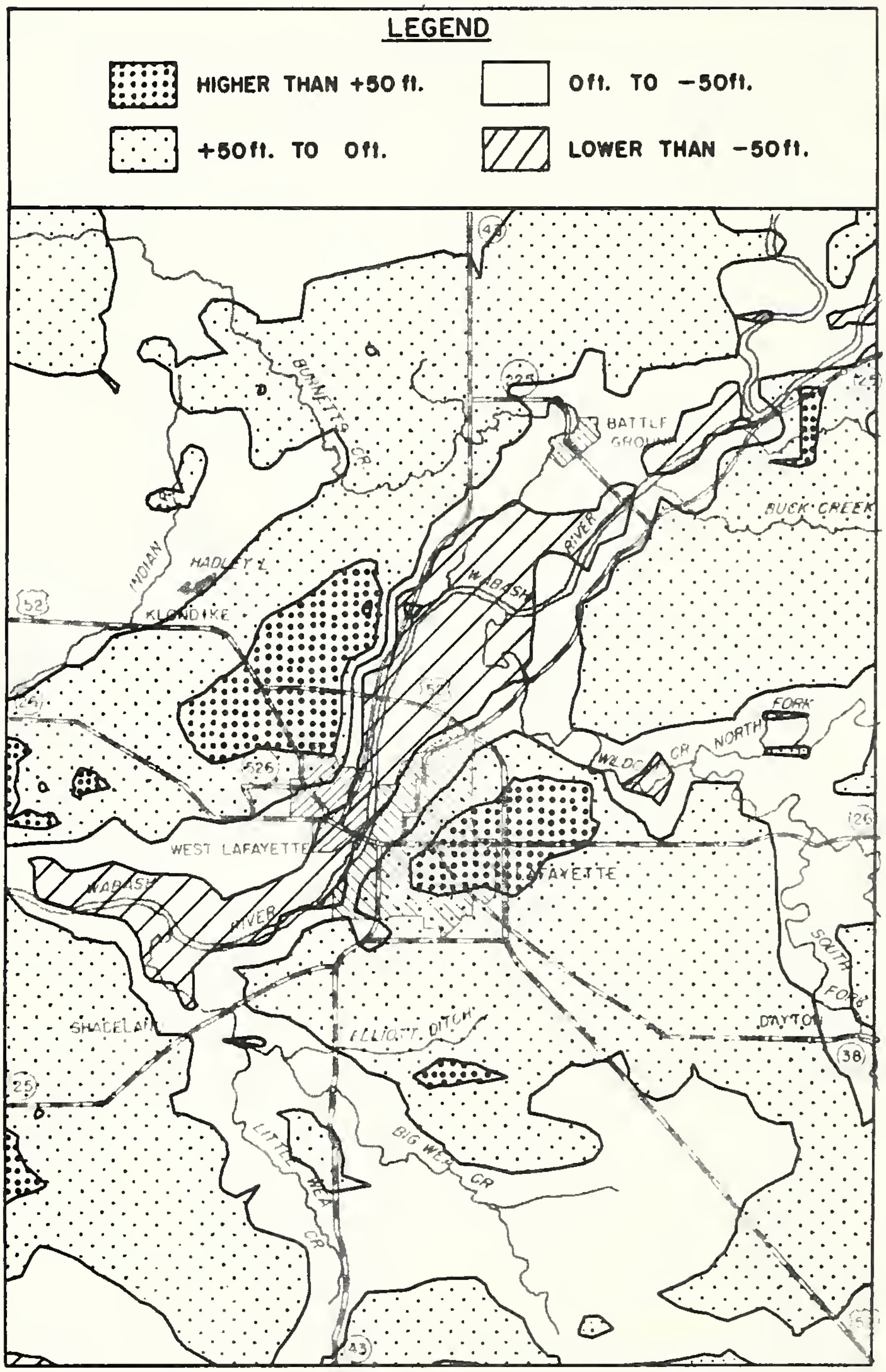


FIGURE 69. NORTHERN TEST AREA - MAP OF RESIDUALS TO FIFTH DEGREE TREND SURFACE FITTED TO ELEVATION DATA.

TABLE 13

NORTHERN TEST AREA PAVEMENT CONSTRUCTION COST VALUES

Engineering Soil Type	Soil Code Number	Ulbricht Mean Rating	Ulbricht quality description	Pavement construction cost-value[*]
Terrace	02	8.7[**]	very good	1.3
Outwash	03	8.5	very good	1.5
Dune Sands	06	7.0	good	3.0
Ridge Moraine	09	4.8	average	5.2
Ground Moraine	07	4.7	average	5.3
Ground Moraine with thin loess	08	4.7	average	5.3
Sandstone and shale	04	4.5	average	5.5
Recent Alluvium	01	4.1	average	5.9
Organic Topsoil and Clay	05	2.0[**]	poor	8.0
Muck	10	0.3	very poor	9.7

[*] Pavement Construction Value Cost = 10.0 - Ulbricht Mean Rating.

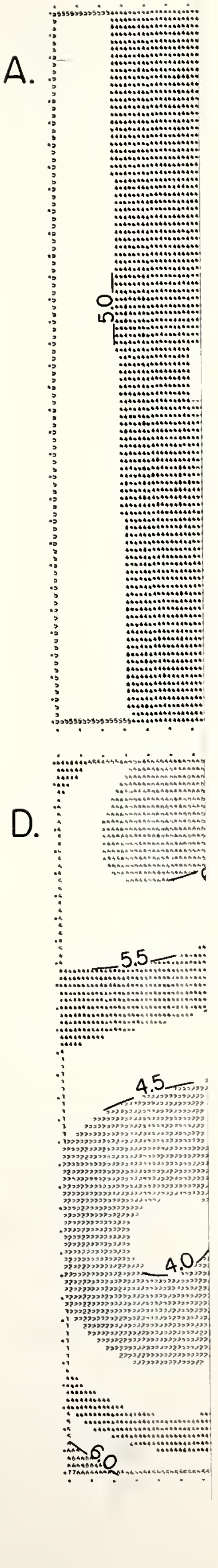
[**] Rating not defined by Ulbricht.

Ulbricht did not separately classify terraces or organic topsoils so appropriate ratings were selected by the author. These mean soil ratings were subtracted from ten to obtain values which increased as the subgrade quality decreased.

Trend surfaces of degree one through five were fitted to the data in order to determine if an appropriate value surface, free from sampling bias, or error, was being obtained. Figure 70 shows the shapes of the pavement construction cost value trend surfaces as displayed by computer-generated contour maps.

Inspection of these maps resulted in a number of conclusions. The first degree surface is almost horizontal (the contour interval for Figure 70-A is 0.1 units; for all the higher degree surfaces it is 0.5 units). There is a very low eastward dip. The surface indicates a lack of any large-scale regional change in soil construction characteristics in the area. In other words it is "uniformly heterogeneous", a fact that can be borne out by personal observation in this area.

The second degree surface forms a quite differently shaped surface. A northeast-southwest trending zone of low pavement cost runs across the map area. This zone reflects the presence of granular terrace and outwash materials along the south of the Wabash River valley. These are rated as good subgrade materials and have low cost values associated with them. The third, fourth, and fifth degree trend surfaces allow this low cost zone to curve from northeast to southwest so as to more nearly follow the Wabash valley. The fifth degree surface shows generally lower values south of the Wabash River compared to those on the north; this appears to reflect the more abundant outwash materials present south of


A.
5.0
D.
5.5
4.5
4.0
6.0

Ulbricht did not separately classify terraces or organic topsoils so appropriate ratings were selected by the author. These mean soil ratings were subtracted from ten to obtain values which increased as the subgrade quality decreased.

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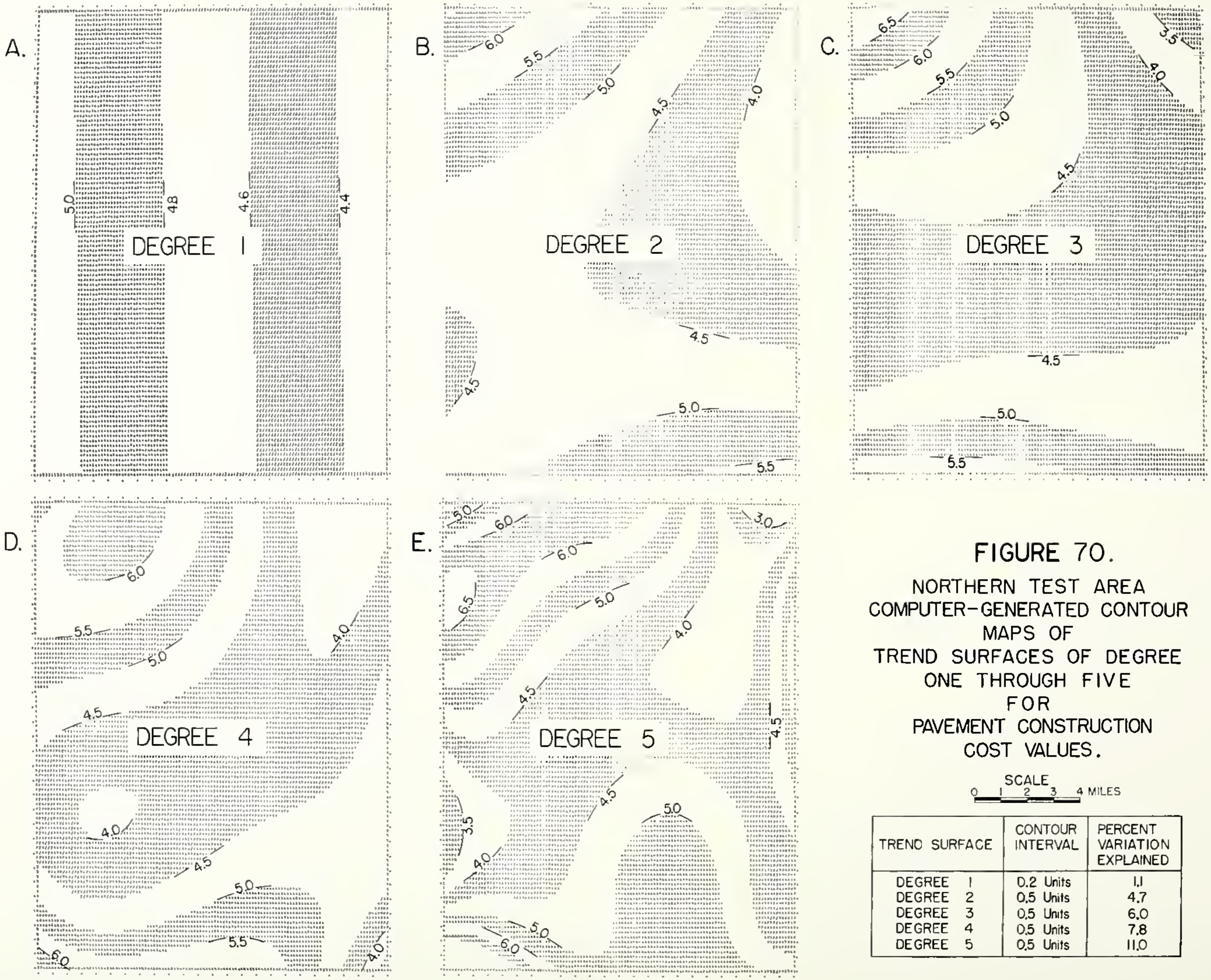


FIGURE 70.

NORTHERN TEST AREA
COMPUTER-GENERATED CONTOUR
MAPS OF
TREND SURFACES OF DEGREE
ONE THROUGH FIVE
FOR
PAVEMENT CONSTRUCTION
COST VALUES.

TREND SURFACE	CONTOUR INTERVAL	PERCENT VARIATION EXPLAINED
DEGREE 1	0.2 Units	1.1
DEGREE 2	0.5 Units	4.7
DEGREE 3	0.5 Units	6.0
DEGREE 4	0.5 Units	7.8
DEGREE 5	0.5 Units	11.0

the river.

Statistical analysis of these trend surfaces, the results of which are found in Table 12 (page 205) reinforced the above conclusions. The percent sum of squares explained by these surfaces is always extremely small, ranging from a little over one percent for the first degree surface to eleven percent for the fifth degree surface. This emphasized the marked local heterogenity of the soil conditions and the lack of any extremely strong regional pavement cost variations. The results of the total and partial F-tests indicate that the various surfaces do represent real effects. The first degree surface has an almost horizontal attitude and the lower confidence levels of its coefficients merely substantiate the earlier statement that there is no significant linear regional pavement construction cost variation in this area. The low partial F-value calculated for the third degree trend surface casts some doubt on its reliability; however this is offset by the higher values obtained for the fourth and fifth degree surfaces which exhibit very similar patterns.

On the basis of this analysis, the pavement construction cost values derived from sampled engineering soil map information and modified by Ulbricht's rating scale were accepted as valid. The percent variation explained by the trend surfaces indicates that large local heterogeneity is present in this data. Accordingly a series of gridded estimates of the sampled pavement construction cost values were computed using a weighted moving average procedure. These were selected to form the pavement construction cost value surface which is shown by a computer-generated contour map in Figure 71.

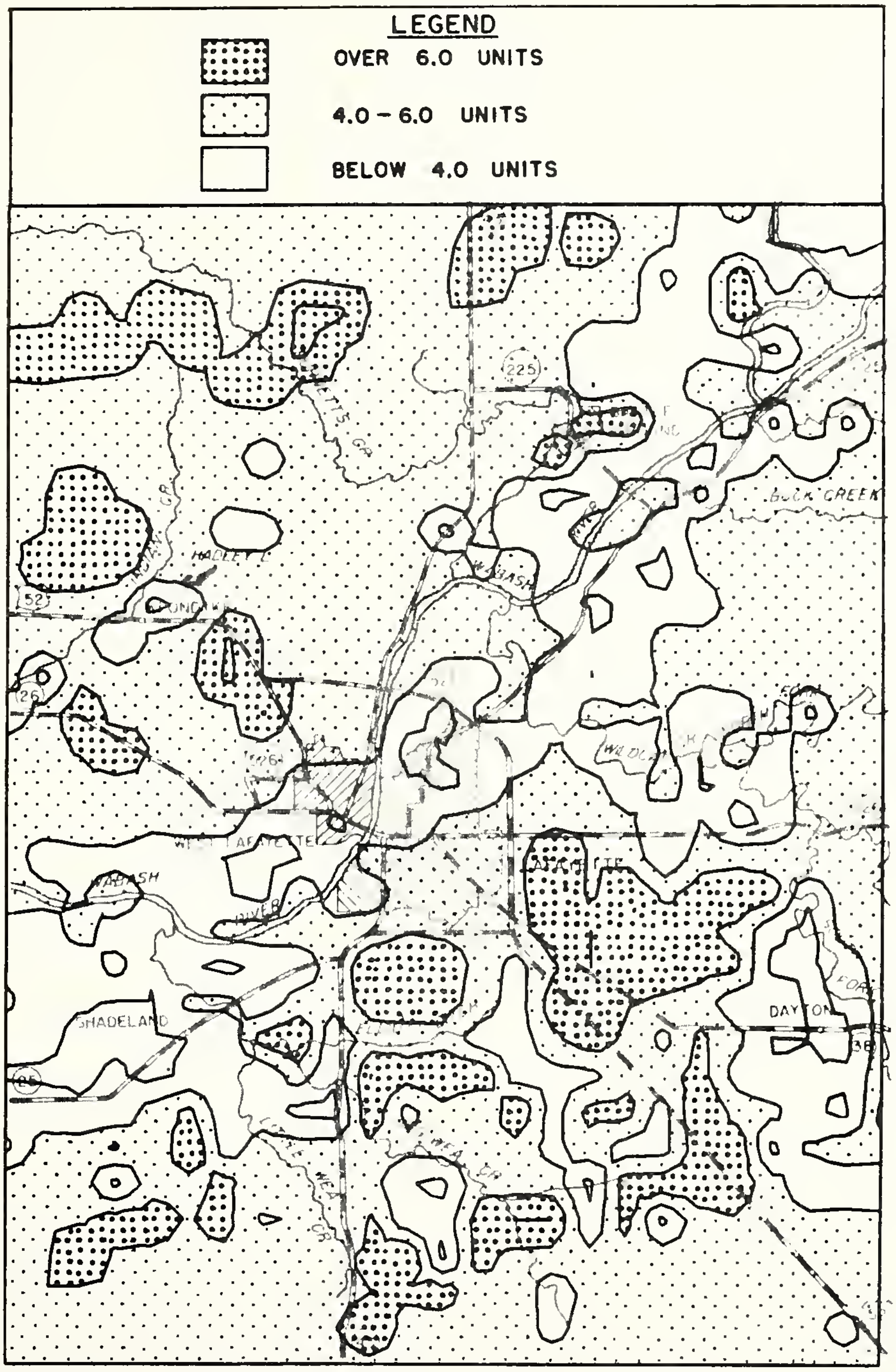


FIGURE 71. NORTHERN TEST AREA - CONTOUR MAP OF PAVEMENT CONSTRUCTION COST VALUE SURFACE.

Derivation of a Value Surface for the Right-of-Way Acquisition Cost Factor

Assessment of all properties within an area as large as the northern test area would be a lengthy and expensive process. Such detailed information is probably unnecessary until the lower alignment level of the highway planning hierarchy is reached. Consideration was given to the following:

(1) Selectively assessing samples of property classes throughout the area.

(2) Extracting assessed valuations from local tax rolls.

(3) Requesting quotations from local real estate companies.

However, legal or practical difficulties were presented which ultimately discouraged these approaches.

With the extremely limited staff available for this project an approximate procedure proved to be the only feasible approach. The author feels the results of the adopted procedure are satisfactory; however it is obvious that more exact procedures would be desirable, particularly if this type of analysis is being performed by agencies having access to data banks, local property tax rolls, or having sufficient staff to collect and compile the necessary information.

The adopted procedure is analogous to that utilized in the southern test area. Changes resulted from the change in scales and necessary detail required by the two studies. As described in Chapter IV the basic measure is a land use map, shown as Figure 31 (page 112). This was developed partly from land use classifications developed for 109 zones by Golenberg [31] and partly by interpretation of 1963 aerial photographs.

Golenberg's data covered the metropolitan areas; the photo interpretation covered the suburban and rural portions of the test area.

Six land use categories were defined for the northern test area on a zone basis. A total of 213 zones were defined. Each land use category was given a code number. The land use data was collected in conjunction with several of the service benefit measures. Thus in accordance with common traffic engineering practice each zone was sampled once with the data measured at the zone centroid.

A rating scale was devised to convert the six land use measures to right of way acquisition cost values by the comparatively simple expedient of polling selected knowledgable Purdue University staff members. The selected scale is given in Table 14. In devising the scale, agricultural land costs of 400 - 600 dollars per acre were assumed to be equal to one. Thus residential land ranging upward from 1000 dollars an acre took a weight of three. The high rating of ten given to institutional and recreational land use categories reflects their general unavailability for right of way acquisition. Recreational land in this area consists primarily of municipal parks.

The rating scheme can be considered to reflect dollar values tempered by an appreciation of social and aesthetic considerations. The enormous range in land values present within many categories is recognized by the author and it is conceded that the rating system can at best be only a crude approximation of actual costs. It is not intended that this rating system be applied in actual location studies, however in the context of the present research it was felt desirable to show how land acquisitions costs, in conjunction with other factors, can affect the choice of highway

TABLE 14

NORTHERN TEST AREA

ADOPTED RATING SCALE FOR RIGHT OF WAY ACQUISITION COST VALUES

Land Use Category*	Code Number	Right of Way Acquisition Cost Value
Agricultural	01	1.0
Residential	02	3.0
Commercial	03	8.0
Industrial	04	9.0
Institutional	05	10.0
Recreational	06	10.0

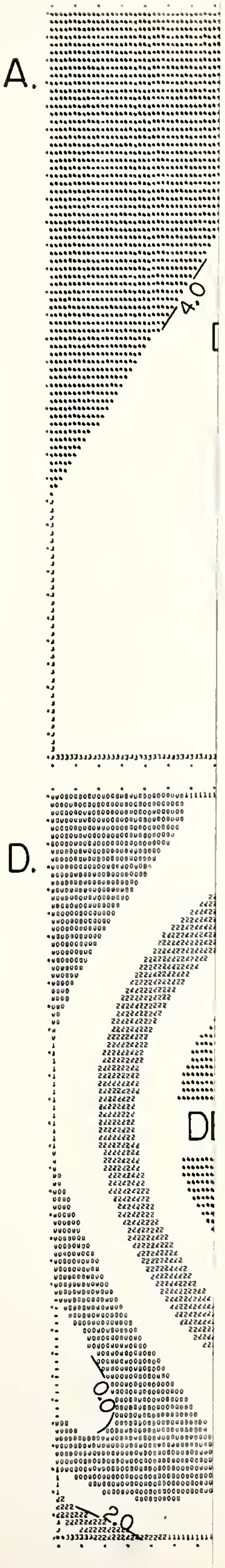
*Land use categories defined by Golenberg or by airphoto interpretation.

locations. The results of the analysis appear reasonable; thus the procedure can be best defended in terms of the results achieved.

Trend surfaces of degrees one through five were fitted to the land acquisition cost values to test their validity. Computer generated contour maps of these trend surfaces are shown in Figure 72. The results of statistical analyses are given in Table 12 (page 205).

The first degree surface is nearly horizontal, sloping gently downward from northwest to southwest. This orientation is probably the result of the Lafayette-West Lafayette metropolitan area being located slightly northwest of true map center and is not believed significant in the light of the statistical analysis. The first degree surface explains less than two percent of the data variability, while both the total and partial F-tests give low confidence to the hypothesis that the linear coefficients are significantly different from zero. Thus little importance is attached to this surface.

The higher degree trend surfaces differ greatly from the first degree surface. All show the same general pattern; a dome-shaped maximum more or less centered over the Lafayette-West Lafayette area. Partial F-test results suggest the second and fourth degree coefficients are the most significant. This is substantiated by the small increases in the percent variation explained which occur in moving from the second to third or fourth to fifth degree trend surfaces. Comparison of the second and fourth degree trend surfaces shows that while the second degree surface poorly fits the data in the corners of the study area, giving large unrealistic negative values, the fourth degree surface is capable of "curling its corners up" and so giving a better over-all fit to the data.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D.
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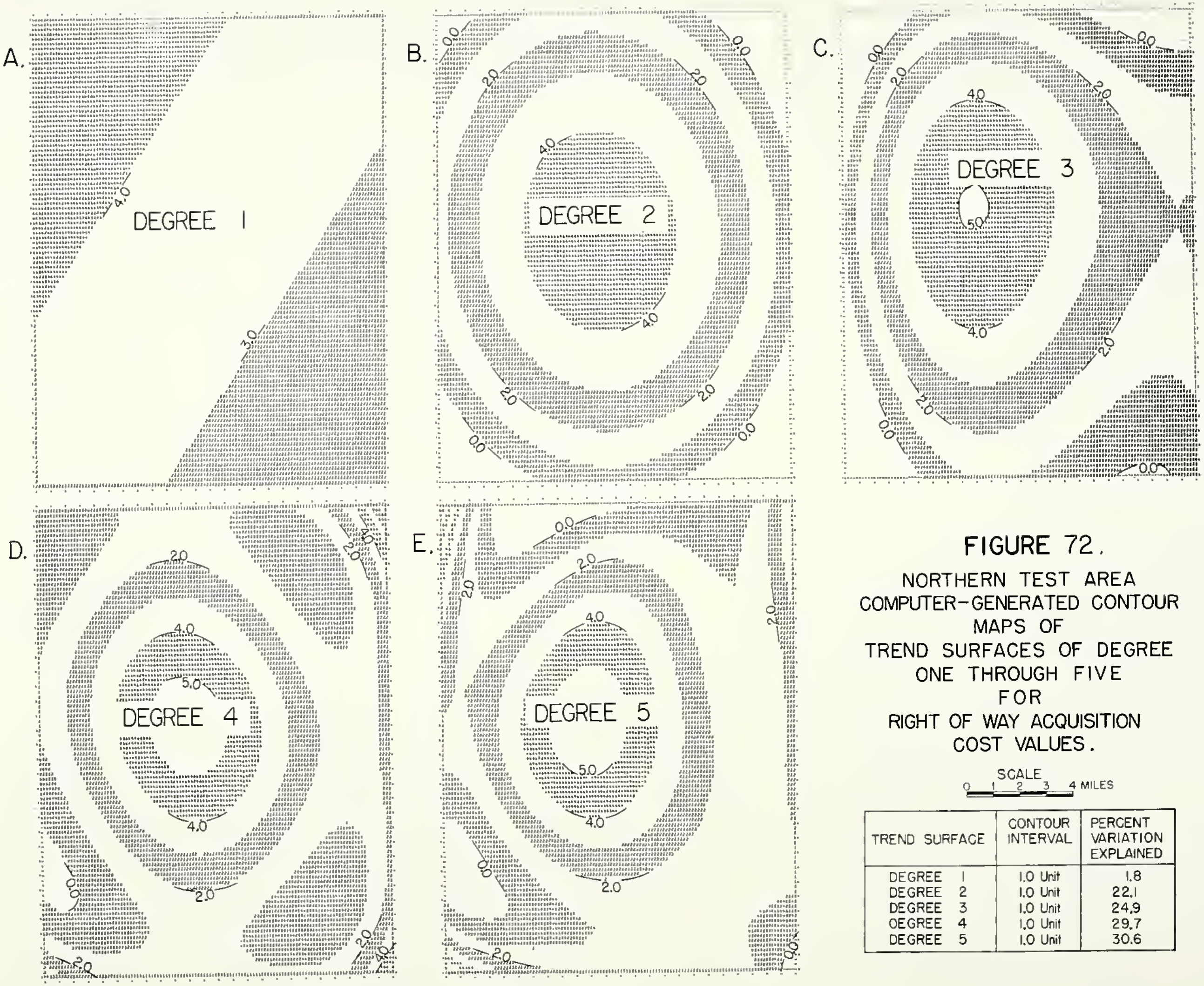


FIGURE 72.
NORTHERN TEST AREA
COMPUTER-GENERATED CONTOUR
MAPS OF
TREND SURFACES OF DEGREE
ONE THROUGH FIVE
FOR
RIGHT OF WAY ACQUISITION
COST VALUES.

TREND SURFACE	CONTOUR INTERVAL	PERCENT VARIATION EXPLAINED
DEGREE 1	1.0 Unit	1.8
DEGREE 2	1.0 Unit	22.1
DEGREE 3	1.0 Unit	24.9
DEGREE 4	1.0 Unit	29.7
DEGREE 5	1.0 Unit	30.6

On the basis of this analysis, the right of way acquisition cost values were accepted. Since the trend surfaces never explained more than 30 percent of the variability in the data, they were not believed suitable substitutes for the sampled values. A series of gridded estimates were therefore computed by a weighted moving average procedure and utilized to form the right of way acquisition cost value surface. This surface is shown by a computer generated contour map in Figure 73.

Derivation of Value Surfaces for the Service Benefits Factor

As shown in Table 4 (page 115) four measures were used to represent some type of service benefit factor. These were (1) population totals, (2) population densities, (3) trip ends, and (4) distribution of present highway facilities. The first three measures were determined for each of 213 orgin-destination zones located within the study area. The distribution of present highway facilities was measured on the Tippecanoe County Highway Map.

Suitable data on population and trip ends were available for the 109 Lafayette metropolitan zones in Golenberg's thesis [31]. Extraction of data from Bureau of the Census PL-1 forms based on the 1960 census was required to extend Golenberg's values to include the entire study area. The census forms tabulate data by census tracts which cover many zones. Population was distributed in rural area zones by the simple expedient of counting the dwellings in a zone and multiplying this figure by the average number of people per dwelling, a statistic listed for each census tract. Values were rounded to the nearest whole person.

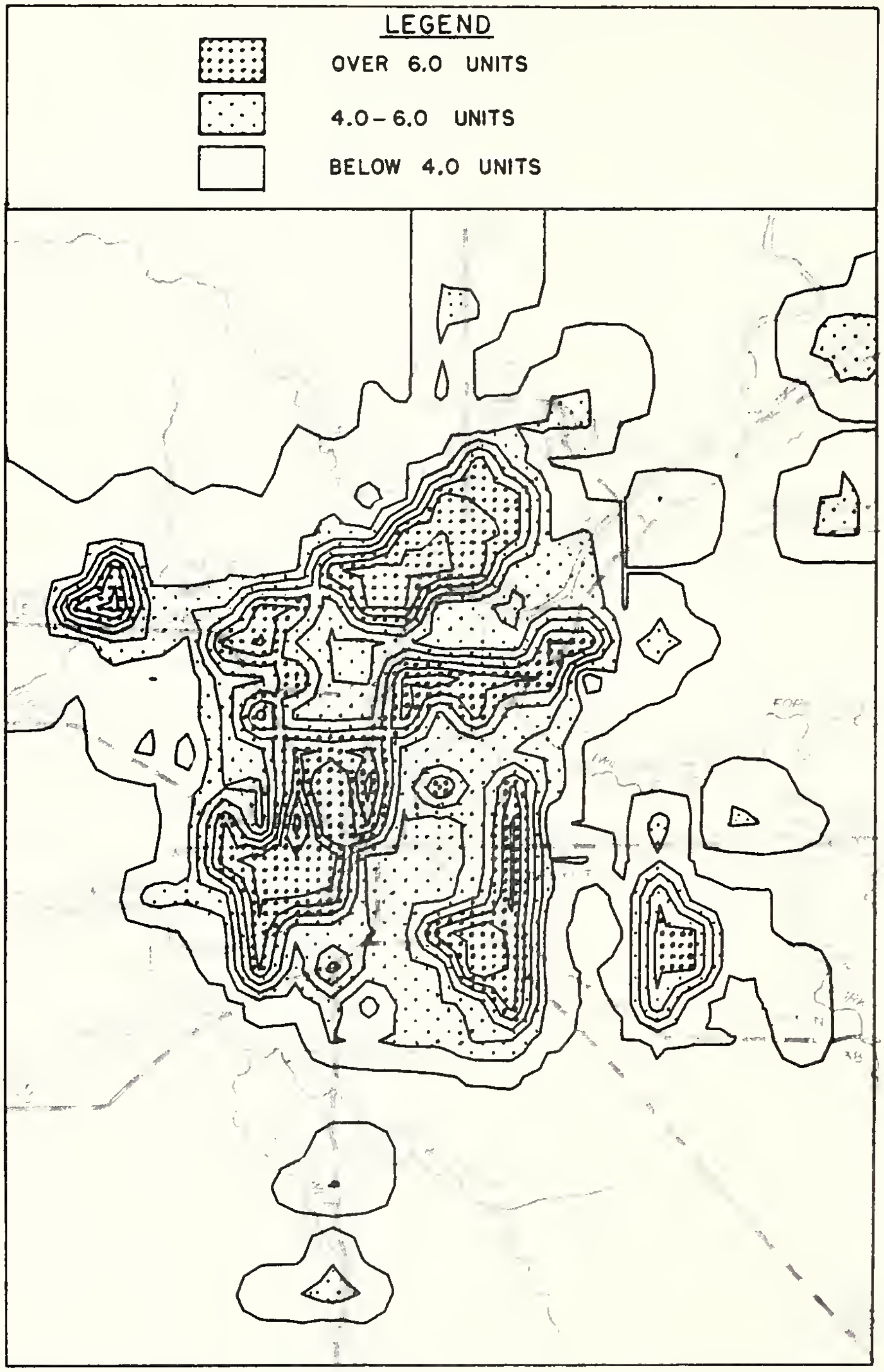


FIGURE 73. NORTHERN TEST AREA-CONTOUR MAP OF RIGHT OF WAY ACQUISITION COST VALUE SURFACE.

For those census tracts which covered suburban as well as rural zones, the rural zones were evaluated first. Progressively more difficult zones were evaluated until all were computed. In those cases where a few zones were very difficult to count because of comparatively dense populations, the remaining populations were arbitrarily distributed in the most reasonable fashion possible. Only a few adjustments were found necessary in order to satisfactorily distribute the population totals for the census tracts among the various zones.

The zone boundaries were initially defined on the 1963 aerial photographs which were assembled to form an uncontrolled mosaic. The boundaries were transferred to a 1:24,000 scale base map drawn from topographic maps. Planimeters were used to measure the areas of each zone in square inches. These figures were converted to acres. The previously determined population totals for each zone were divided by the zone areas to determine population densities measured as people per acre.

Another measure of the demand for transportation is the number of trip ends located in each zone. Industrial and commercial zones demand considerable transportation services, yet few people live in these areas. Thus population data tend to inadequately estimate the demands of commercial or industrial zones. Golenberg developed trip end distributions for 109 urban area zones by taking 1952 trip end values and modifying them by suitable growth models. A number of models were investigated, but it was concluded, on the basis of comparison with screen line counts, that a Fratar distribution with a certain growth factor (termed the Fratar Growth Factor 3) was the best model [31]. Accordingly, trip end distributions developed by this model were used in the current research.

Trip end distributions had to be calculated for the surrounding areas however. These areas are classified as either residential or agricultural. The latter for trip generation purposes was considered to be a low density residential land use. Golenberg reviews a number of techniques for estimating trip generation potentials. The simplest procedures involve the determination by regression analysis of empirical equations relating measurable characteristics, such as population density or vehicle ownership, to the number of trips. Shuldiner [102] developed prediction equations for trip generation from the home. The following equation developed by Shuldiner was used in this study:-

$$T = -0.627 + 1.216p$$

T is the average daily number of person trips from a home and p is the number of persons per dwelling unit. The value of p for each census tract, and thus for each zone, is available on the census forms. It was thus a simple matter to obtain T. The total number of trip ends in a zone was merely the value of T multiplied by the number of housing units per zone; a value that had already been determined.

Evaluation of these measures of the service benefit factor, namely the zone population totals, the zone population densities and the zone trip ends, involved considerable effort. Accordingly, as in the southern test area, a measure of the quality of the existing road network was investigated as an alternative. The ratings assigned to each type of roadway are shown in Table 15. The quality of each road intersection equals the sum of the ratings of the roadways meeting at the intersection. Values of the road intersections range from 3.0 for a "Tee" intersection involving gravel roads to 20.0 for an intersection between two principal

TABLE 15

ROADWAY RATINGS FOR NORTHERN TEST AREA

Roadway Classification*	Rating
US 52 and US 52 Bypass	6
Federal and Primary State Highways	4
Secondary State Highways	3
Urban Arterials	3
Rural, Bituminous Surfaced	2
Rural, Gravel Surfaced	1

*Roads classified according to Tippecanoe County Highway Map.

highways. The intersections were sampled as a discrete measure on the Tippecanoe County Highway Map (revised 1966 edition) scaled at one inch to the mile. A total of 402 intersections were evaluated. Generation of these values was extremely rapid in comparison with the time required to develop the other measures.

Trend surfaces of degree one through five were fitted to all four data sets in order to test the value surfaces for accuracy and lack of bias. All four values gave very similar results as shown by the statistics in Tables 16 and 17. Figure 74 shows computer generated contour maps of the five trend surfaces fitted to the trip ends data.

None of these first degree trend surfaces are statistically significant. The second, third, fourth and fifth degree surfaces form domes centered on the Lafayette metropolitan area. The higher degree surfaces show a greater ability to "curl up their corners" and avoid the unrealistic large negative values in the corners. The higher degree surfaces of the road intersection quality values show high values toward the southeast and west along US Route 52. Higher values are found also in the northeast reflecting the presence of Indiana State Route 25.

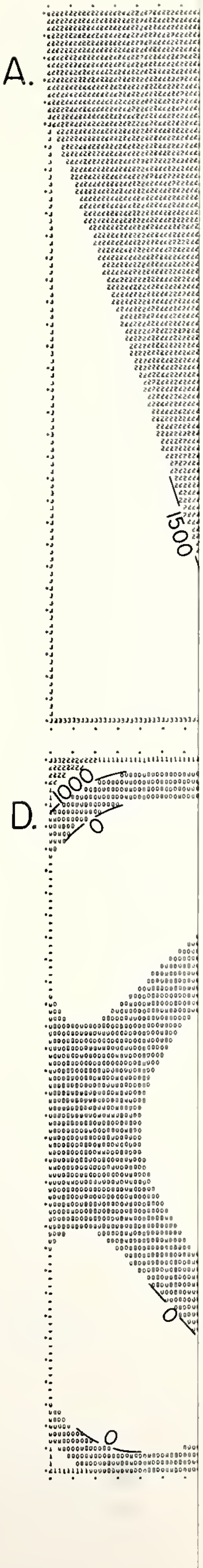
None of the trend surfaces explained a very high percentage of the total variability inherent in the original data. Thus the value surfaces for each measure were represented by a series of gridded values, interpolated from the original sampled values by a weighted moving average procedure. These value surfaces are shown in Figures 75 and 76.

In order to measure the apparent similarity of the various service benefit factor value surfaces, the gridded values were studied by the map comparison techniques described by Tobler [112]. For purposes of

TABLE 16

NORTHERN TEST AREA - RESULTS OF STATISTICAL ANALYSES - II

Values or Measures	Degree of Trend Surface	Analysis of Variance						
			Total F-Tests			Partial F-Tests of Highest Degree Trend		
		Percent Variation Explained	Degrees of Freedom	Computed F-Value	Level of Significance (1-α)	Degrees of Freedom	Computed F-Value	Level of Significance (1-α)
Population Totals for Origin-Destination Zones	1	.3	3,209	0.2	.10	2,210	0.4	.25
	2	10.0	6,206	3.8	.99	3,209	7.7	.99
	3	12.1	10,202	2.8	.99	4,208	1.2	.50
	4	17.5	15,197	2.8	.99	5,207	2.6	.975
	5	19.4	21,191	2.2	.99	6,206	0.7	.50
Population Densities for Origin-Destination Zones	1	0.8	3,209	0.6	.25	2,210	1.0	.50
	2	12.7	6,206	5.0	.99	3,209	10.1	.99
	3	15.4	10,202	3.7	.95	4,208	1.7	.75
	4	22.4	15,197	3.8	.99	5,207	3.6	.99
	5	25.0	21,191	3.0	.99	6,206	1.1	.50
Trip Ends for Origin-Destination Zones	1	0.5	3,209	0.4	.25	2,210	0.6	.25
	2	12.2	6,206	4.8	.99	3,209	9.5	.99
	3	14.0	10,202	3.3	.99	4,208	1.1	.50
	4	19.6	15,197	3.2	.99	5,207	2.7	.975
	5	21.6	21,191	2.5	.99	6,206	0.8	.25
Road Intersection Quality Ratings	1	0.3	3,398	0.4	.25	2,399	0.8	.50
	2	25.1	6,395	22.1	.99	3,398	51.2	.99
	3	27.2	10,391	14.6	.99	4,397	3.3	.99
	4	36.7	15,386	14.9	.99	5,396	11.7	.99
	5	38.6	21,380	11.4	.99	6,395	2.0	.90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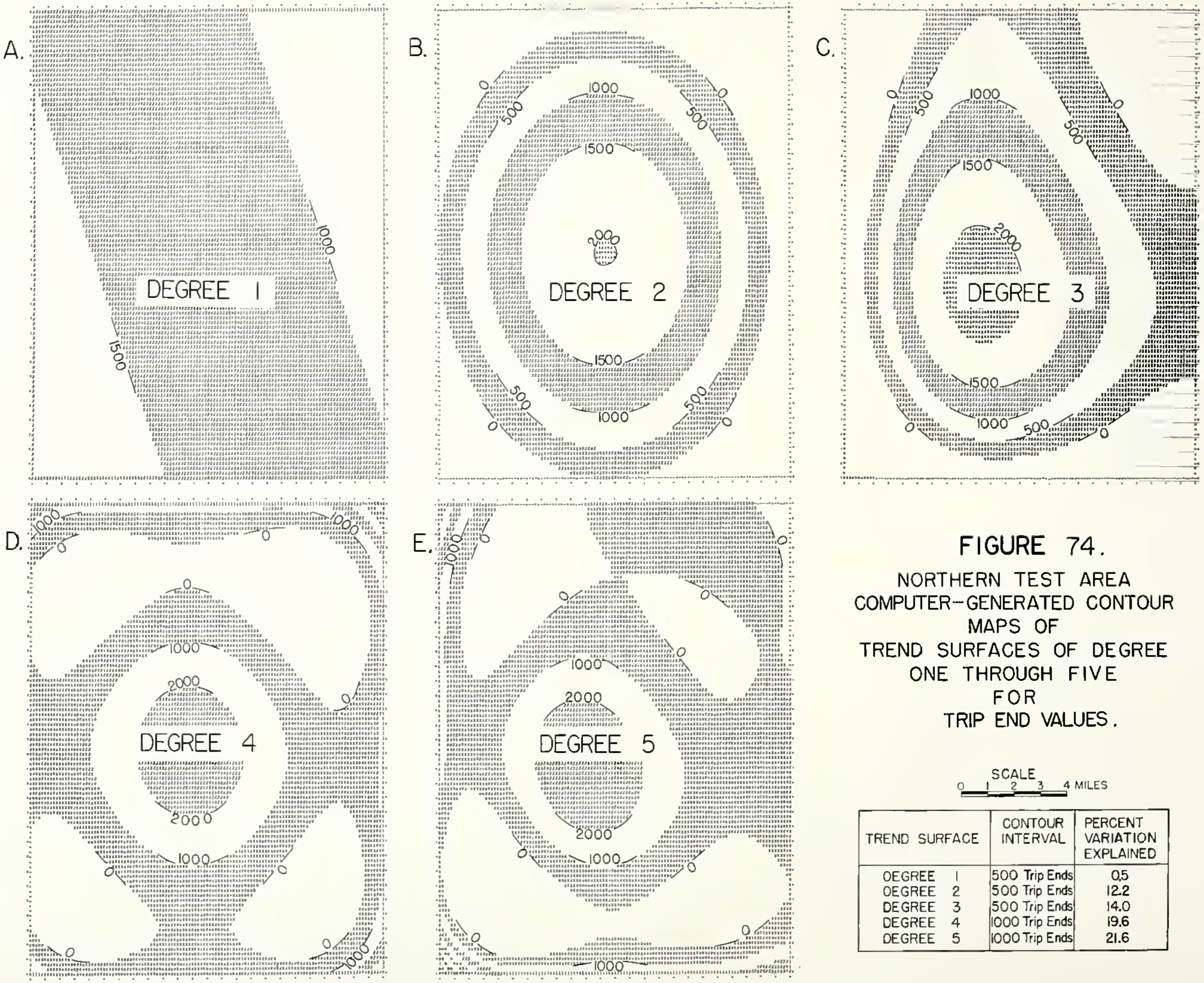


FIGURE 74.

NORTHERN TEST AREA
COMPUTER-GENERATED CONTOUR
MAPS OF
TREND SURFACES OF DEGREE
ONE THROUGH FIVE
FOR
TRIP END VALUES.

SCALE
0 1 2 3 4 MILES

TREND SURFACE	CONTOUR INTERVAL	PERCENT VARIATION EXPLAINED
DEGREE 1	500 Trip Ends	0.5
DEGREE 2	500 Trip Ends	12.2
DEGREE 3	500 Trip Ends	14.0
DEGREE 4	1000 Trip Ends	19.6
DEGREE 5	1000 Trip Ends	21.6

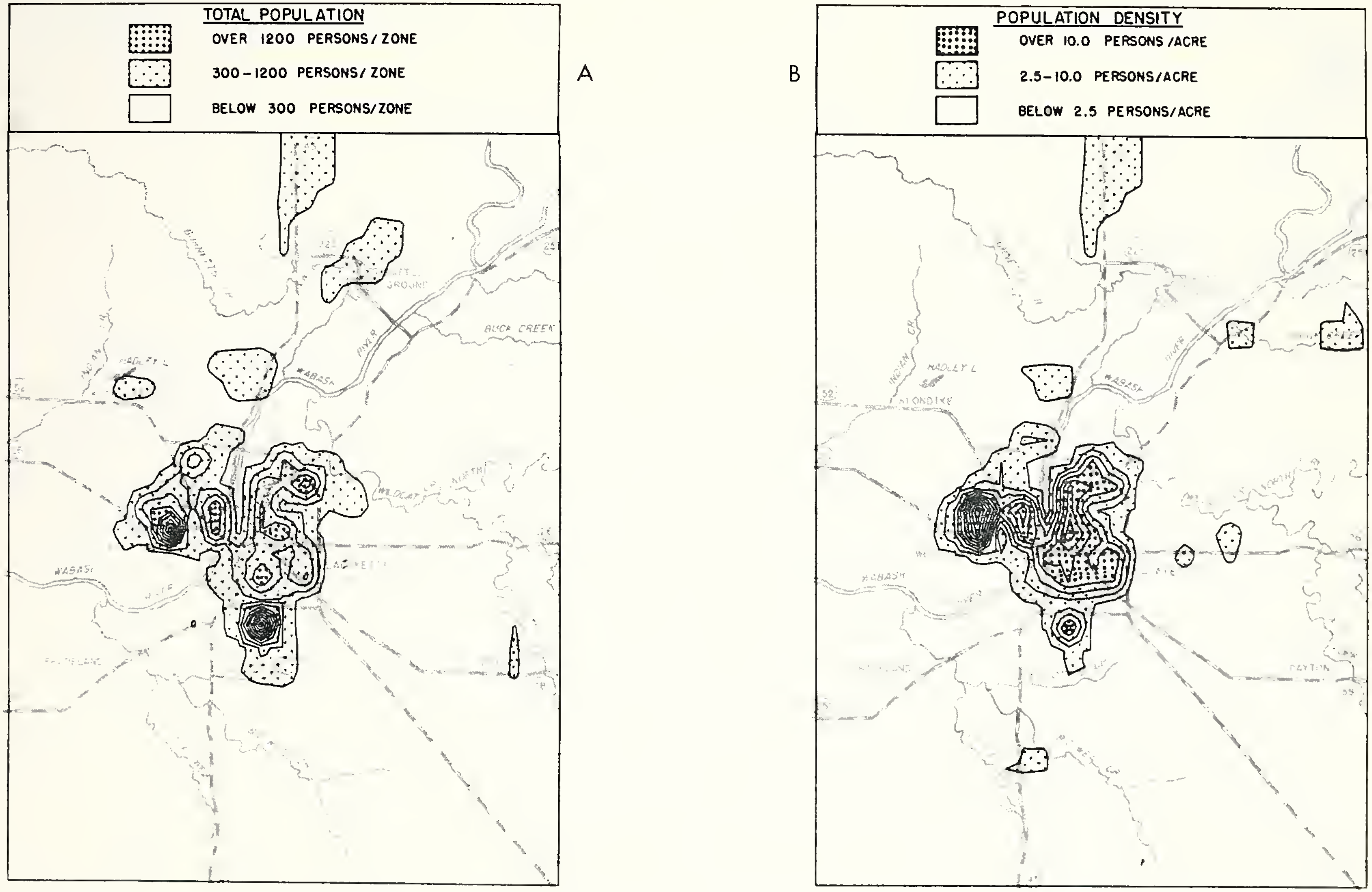


FIGURE 75. NORTHERN TEST AREA - CONTOUR MAPS OF TOTAL POPULATION AND POPULATION DENSITY VALUE SURFACES.

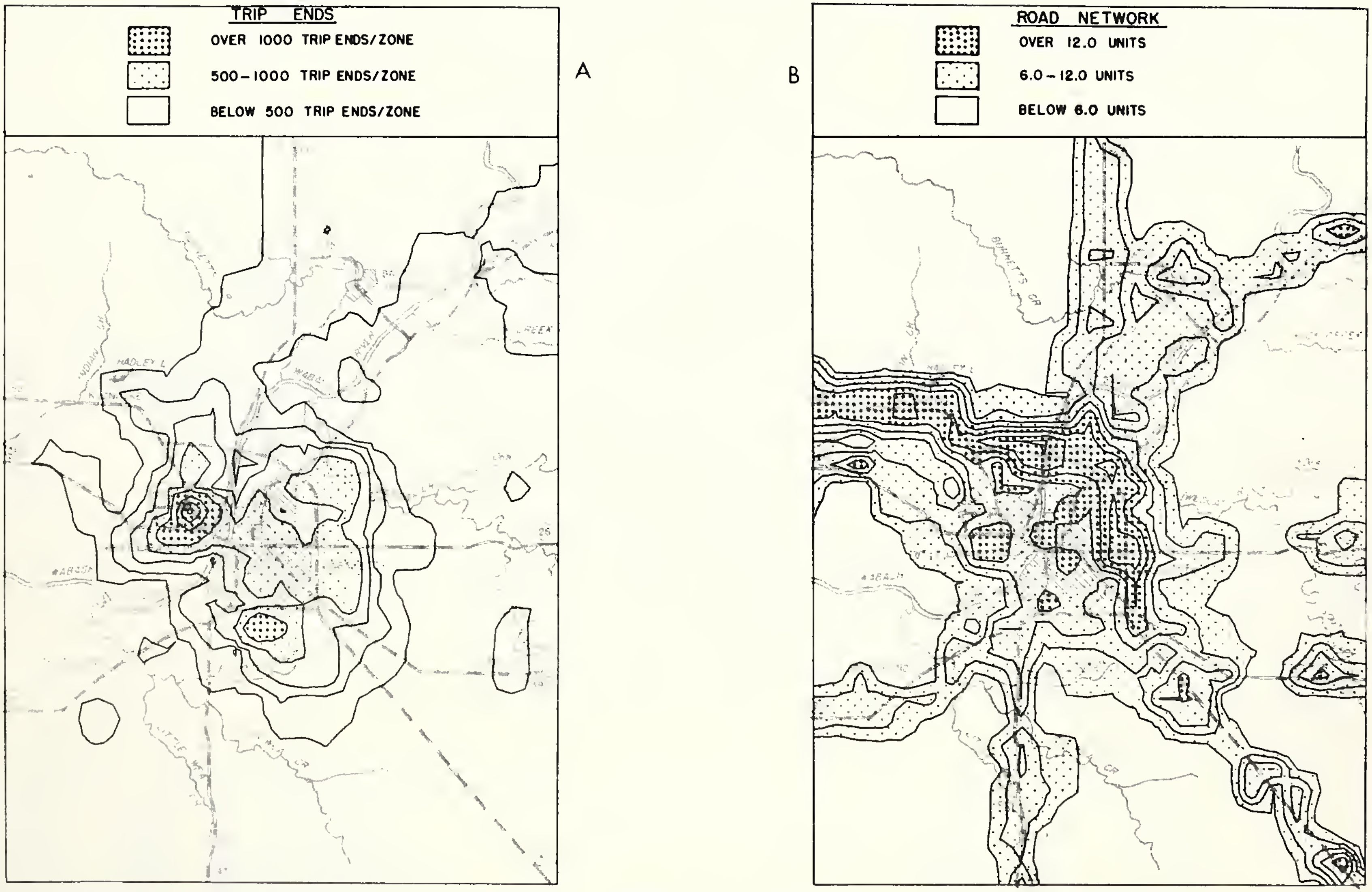


FIGURE 76. NORTHERN TEST AREA- CONTOUR MAPS OF TRIP ENDS AND ROAD NETWORK VALUE SURFACES.

TABLE 17

CORRELATION COEFFICIENTS DETERMINED BY COMPARISON OF FIVE VALUE SURFACES

	Road Intersection Quality	Trip Ends	Population Density	Population Totals	Right of Way Acquisition Cost
Road Intersection Quality	1.000				
Trip Ends	0.400	1.000			
Population Density	0.399	0.583	1.000		
Population Totals	0.370	0.602	0.852	1.000	
Right of Way Acquisition Cost	0.530	0.398	0.301	0.234	1.000

comparison, the right of way acquisition cost values were also included.

The method yields a series of linear correlation coefficients which are displayed in Table 17. The procedure is sensitive to small discrepancies between the surfaces being compared however, and so the computed coefficients are not particularly high. This indicates that each value surface forms a distinct service benefit factor. Accordingly each of these data sets were converted to utilities and used to generate alternative highway locations.

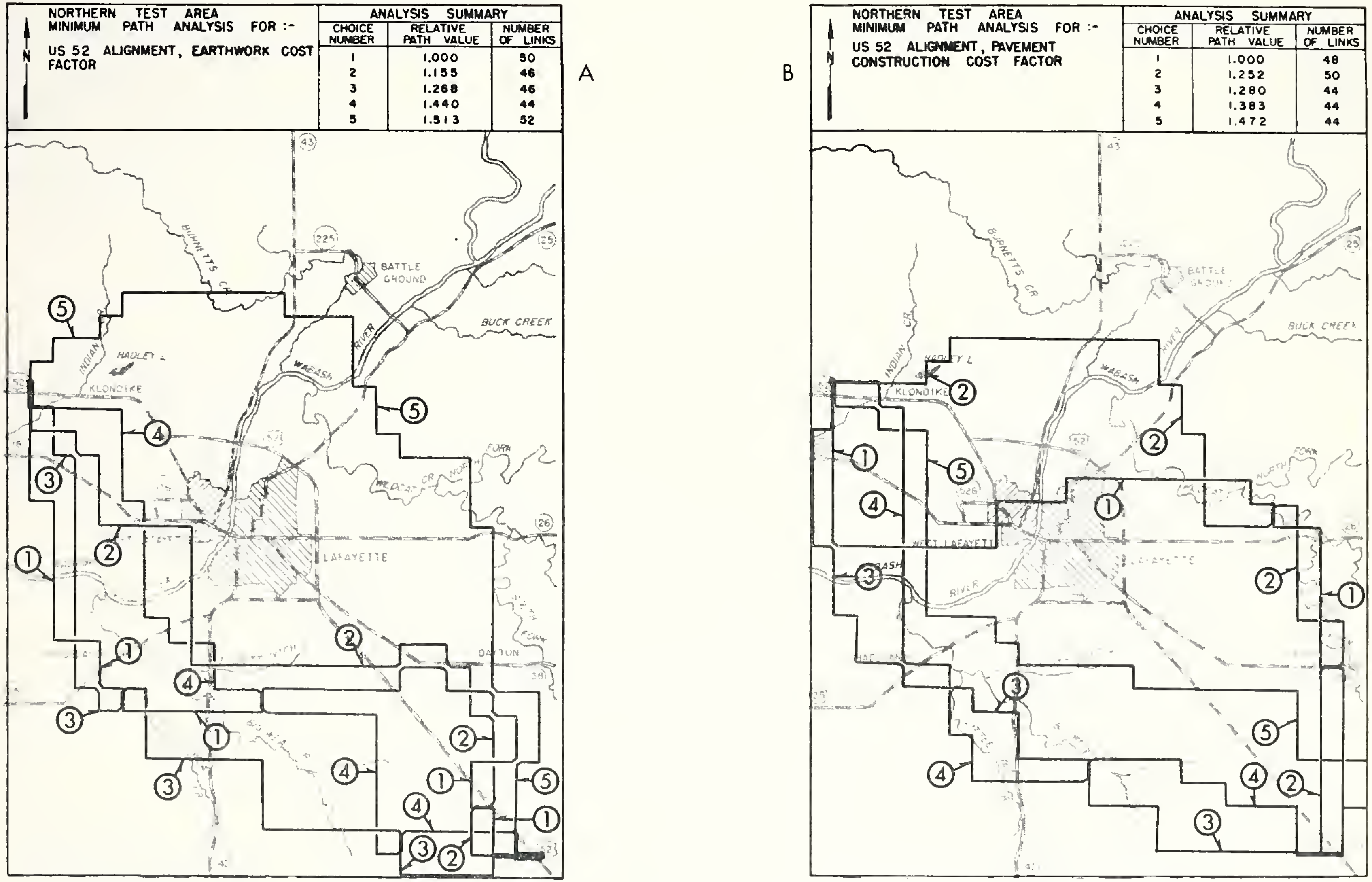
Generation of Single Factor Alternatives

Before the generation of alternatives can begin, an origin and a destination must be selected. A single origin and destination will, at this level in the highway planning hierarchy, define a Route.

After consideration of the transportation needs of the area, and of its probable future needs, it was decided to evaluate two routes; the first joining US 52 southeast of Lafayette to US 52 northwest of West Lafayette, the second joining State Road 43 south of Lafayette with State Road 43 north of West Lafayette.

Results of Analysis for US 52 Route

Figures 77, 78, 79, and 80 show the results obtained for the US 52 route. Alternatives generated to minimize earthwork costs, Figure 77-A, generally lie south and west of the Lafayette-West Lafayette metropolitan area. Cost increase fairly rapidly from the minimum (first) choice. The second choice costs over 15 percent more, the third almost 29 percent, and the fifth over 50 percent more than the first choice. The competing eastern route is not chosen until the fifth choice. All choices tend to



A

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
US 52 ALIGNMENT, EARTHWORK COST FACTOR

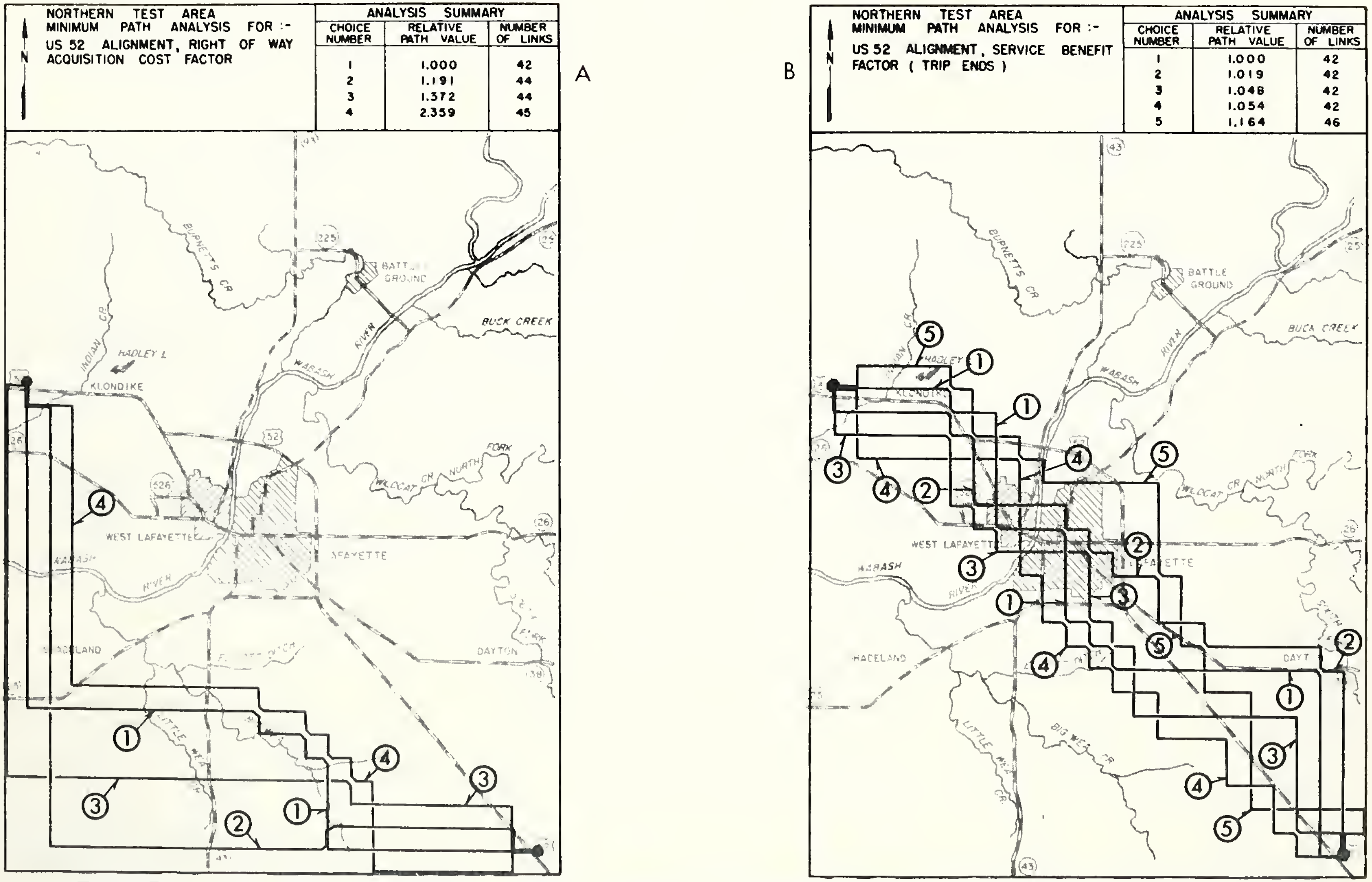
ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	50
2	1.155	46
3	1.268	46
4	1.440	44
5	1.513	52

B

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
US 52 ALIGNMENT, PAVEMENT CONSTRUCTION COST FACTOR

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	48
2	1.252	50
3	1.280	44
4	1.383	44
5	1.472	44

FIGURE 77. NORTHERN TEST AREA - GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.



A

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
US 52 ALIGNMENT, RIGHT OF WAY ACQUISITION COST FACTOR

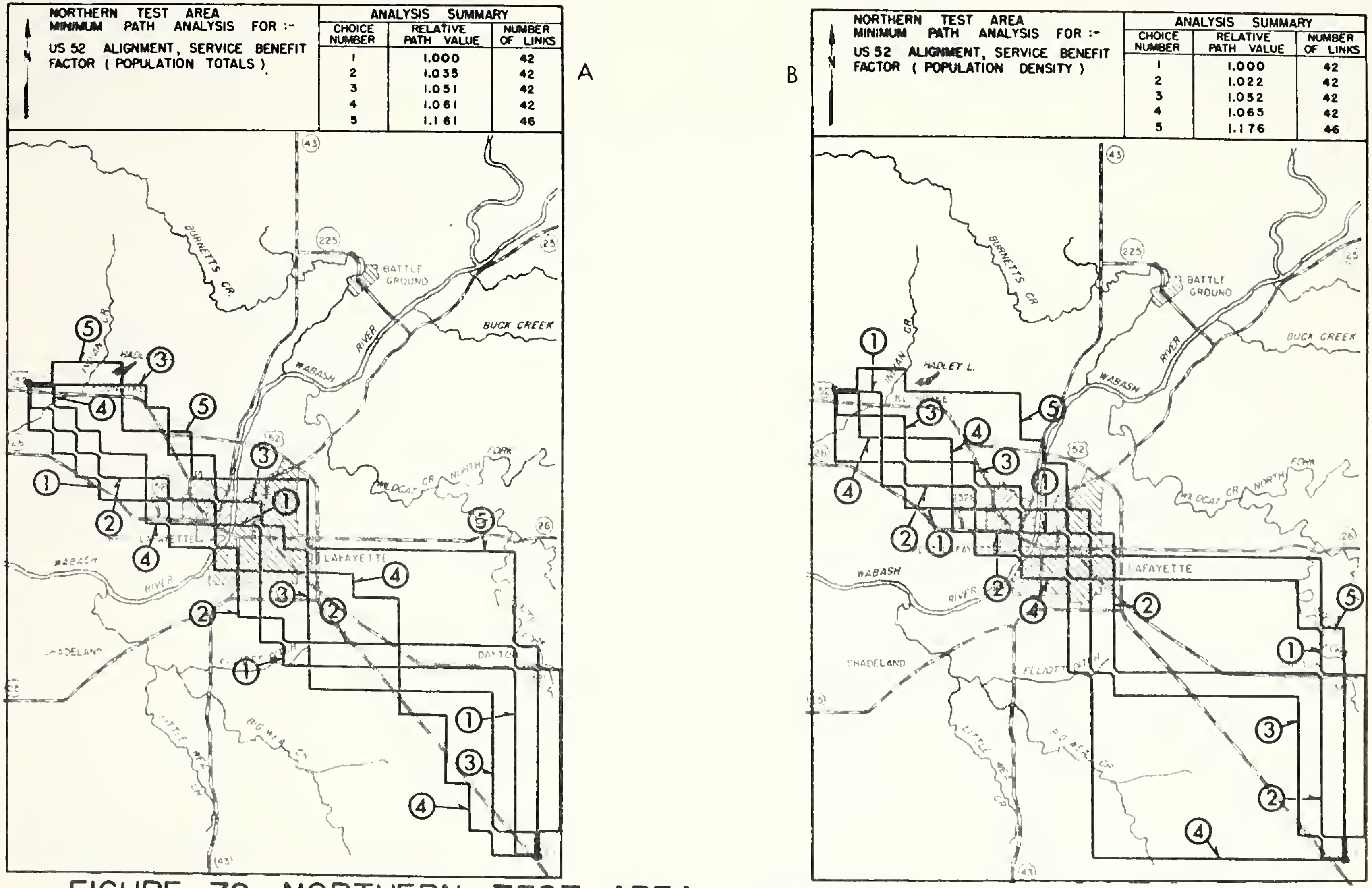
ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.191	44
3	1.372	44
4	2.359	45

B

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
US 52 ALIGNMENT, SERVICE BENEFIT FACTOR (TRIP ENDS)

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.019	42
3	1.048	42
4	1.054	42
5	1.164	46

FIGURE 78. NORTHERN TEST AREA - GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.



NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
US 52 ALIGNMENT, SERVICE BENEFIT FACTOR (POPULATION TOTALS).

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.035	42
3	1.051	42
4	1.061	42
5	1.161	46

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
US 52 ALIGNMENT, SERVICE BENEFIT FACTOR (POPULATION DENSITY)

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.022	42
3	1.052	42
4	1.065	42
5	1.176	46

FIGURE 79. NORTHERN TEST AREA - GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.

A

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR .-
US 52 ALIGNMENT, SERVICE BENEFIT FACTOR (MAXIMIZATION OF PRESENT ROAD NET)

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.409	46
3	1.674	42
4	1.759	42
5	1.929	44

B

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR .-
US 52 ALIGNMENT, SERVICE BENEFIT FACTOR (NON-DUPLICATION OF FACILITIES)

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	48
2	1.005	42
3	1.101	66
4	1.207	44
5	1.290	48

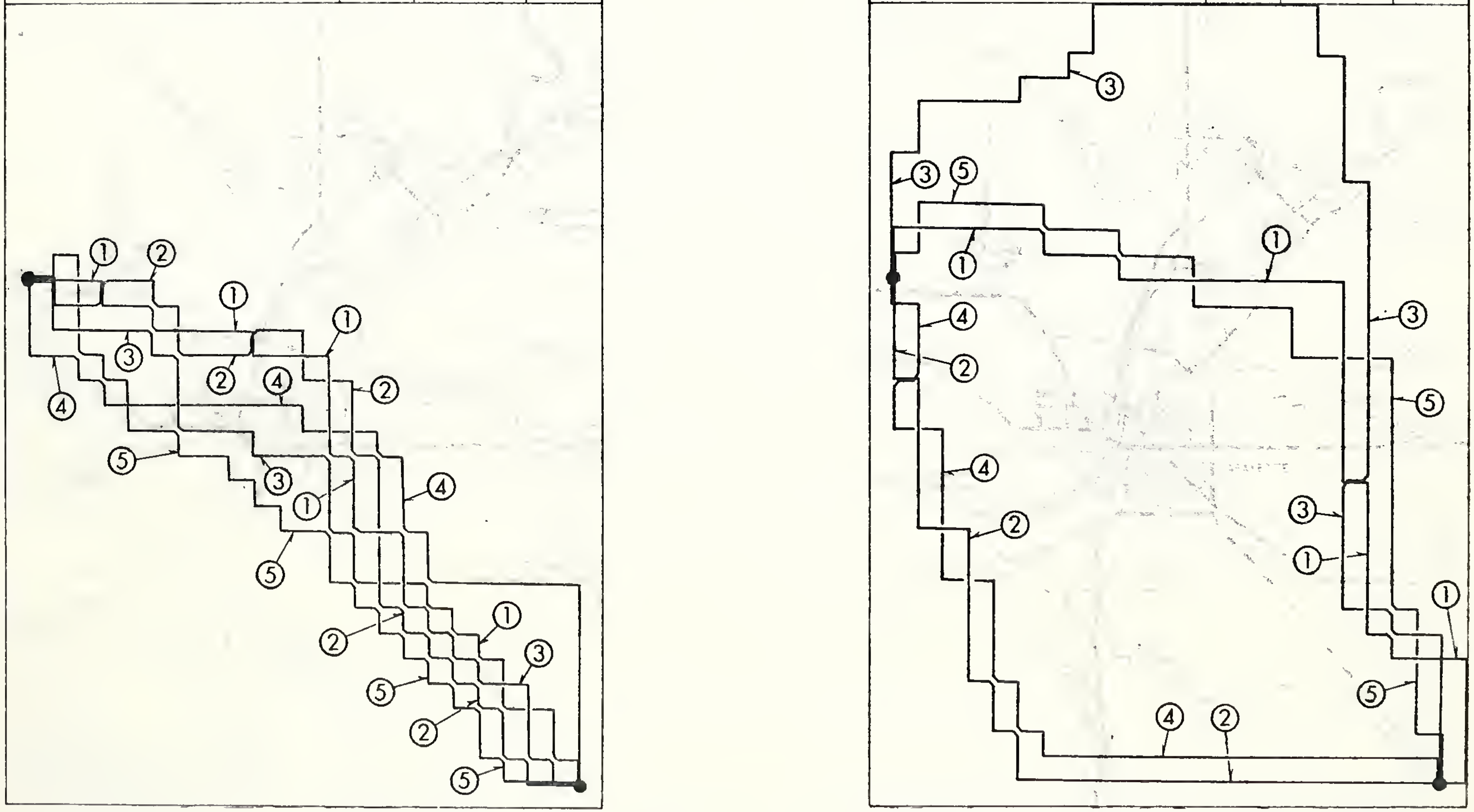


FIGURE 80. NORTHERN TEST AREA-GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.

follow natural depressions when approaching the Wabash Valley.

Figure 77-B shows those alternates generated to minimize pavement construction costs. Examination of the generated alternatives shows they are greatly affected by the presence of granular materials in terraces or outwash plains. Thus the first choice follows Wildcat Creek, and the terraces along the Wabash River before striking due north to its destination north of West Lafayette. Choice two follows Wildcat Creek, crosses the Wabash Valley on the terraces southwest of Battle Ground, then follows the outwash deposits found along the Hadley Lake depression to its destination. Choices three, four, and five follow the outwash plain south of Lafayette onto the Wea plains to the west, before travelling north to their destination.

Figure 78-A shows the generated alternatives which minimize right of way acquisition costs. A marked preference for the western route is evident. The costs of the alternatives rise rapidly with the fourth choice exceeding 235 percent of the first choice.

The analyses designed to measure service benefits using population zone totals, zone population densities, zone trip ends, and maximizing the present road network give very similar results, as shown in Figures 78-B, 79-A, 79-B, and 80-A. As would be expected, all pass through the Lafayette-West Lafayette area. Only small difference exist between the results shown for these four measures.

It is interesting to note that the trip ends data (Figure 78-B) moves the first and second choices further to the north and northwest of West Lafayette, nearer the present US 52 alignment. It is speculated that travel demand from a Purdue Research Park and a large commercial area has caused this effect. Similarly, the maximization of the present road network pushes (Figure 80-A) the early choices nearer the present US 52 bypass, as should be expected. With the exception of the road net maximization analysis where the fifth choice "costs" almost twice the first choice, the range in variation between the generated alternatives for the service benefit factor do not show a sharply defined optimum. The fifth choice for instance does not exceed 118 percent of the first choice.

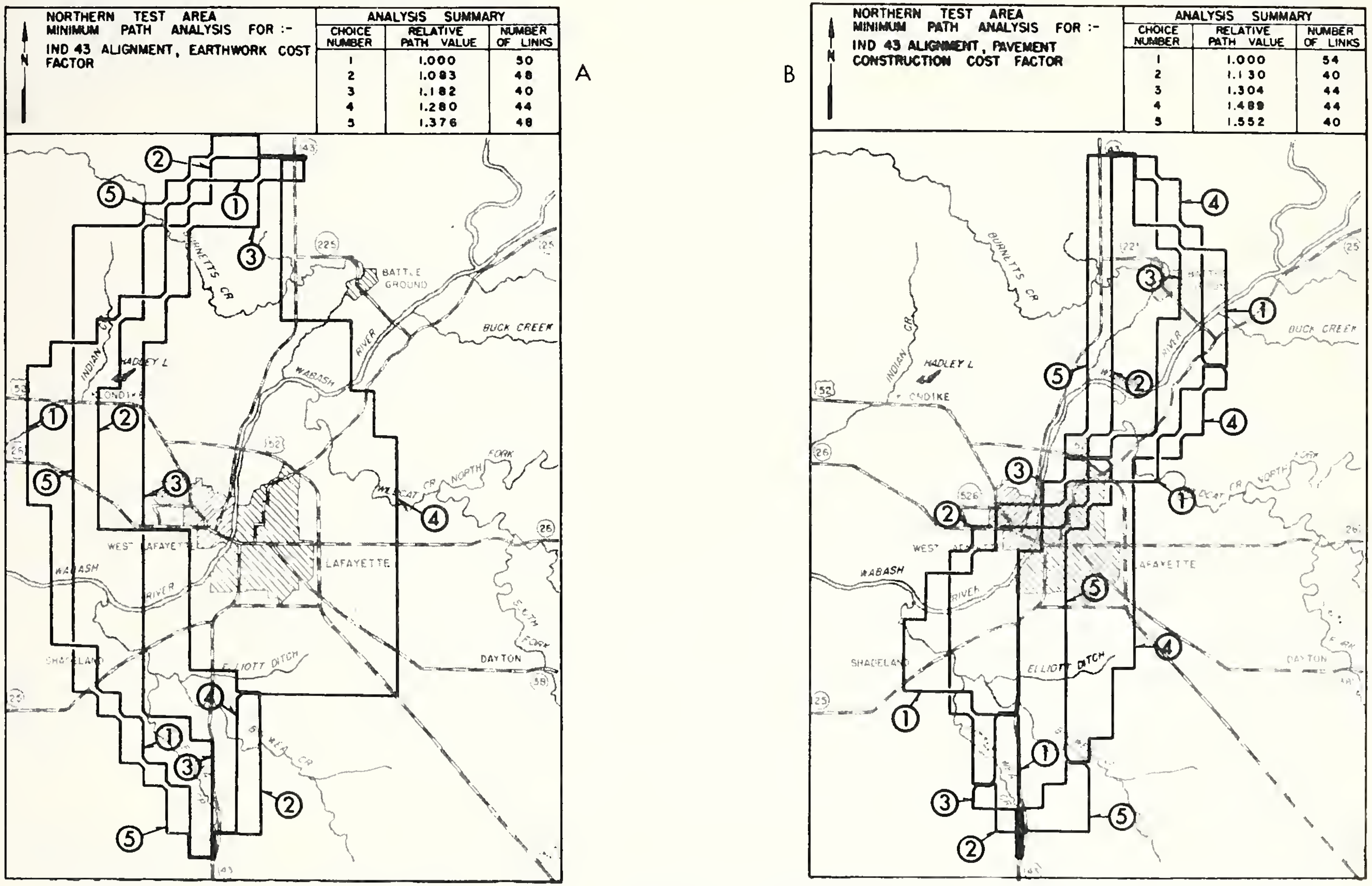
It is possible to consider another type of benefit through use of the road intersection quality values. A new bypass facility should not duplicate present facilities but should be placed so as to best serve the transportation needs in conjunction with present roadways, rather than in competition with them. This can be studied by utilizing the road intersection quality values as a cost rather than a benefit; by seeking routes which minimize these values rather than those which maximize them.

This analysis was performed for the US 52 route. Figure 80-B shows the results. Two alternative routes are developed, with choices one, three, and five favoring an eastern route and choices two and four a western route. The western choices are shorter however.

Results of Analysis for State Road 43 Route

The results of the State Road 43 route analysis for each individual factor are shown in Figures 81, 82, 83, and 84.

The alternatives generated to minimize earthwork costs are shown in Figure 81-A. A western route is favored, with only the fourth choice following an eastern route. The optimum is quite well defined, with the fifth choice costing almost 138 percent of the first choice.



A

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
IND 43 ALIGNMENT, EARTHWORK COST FACTOR

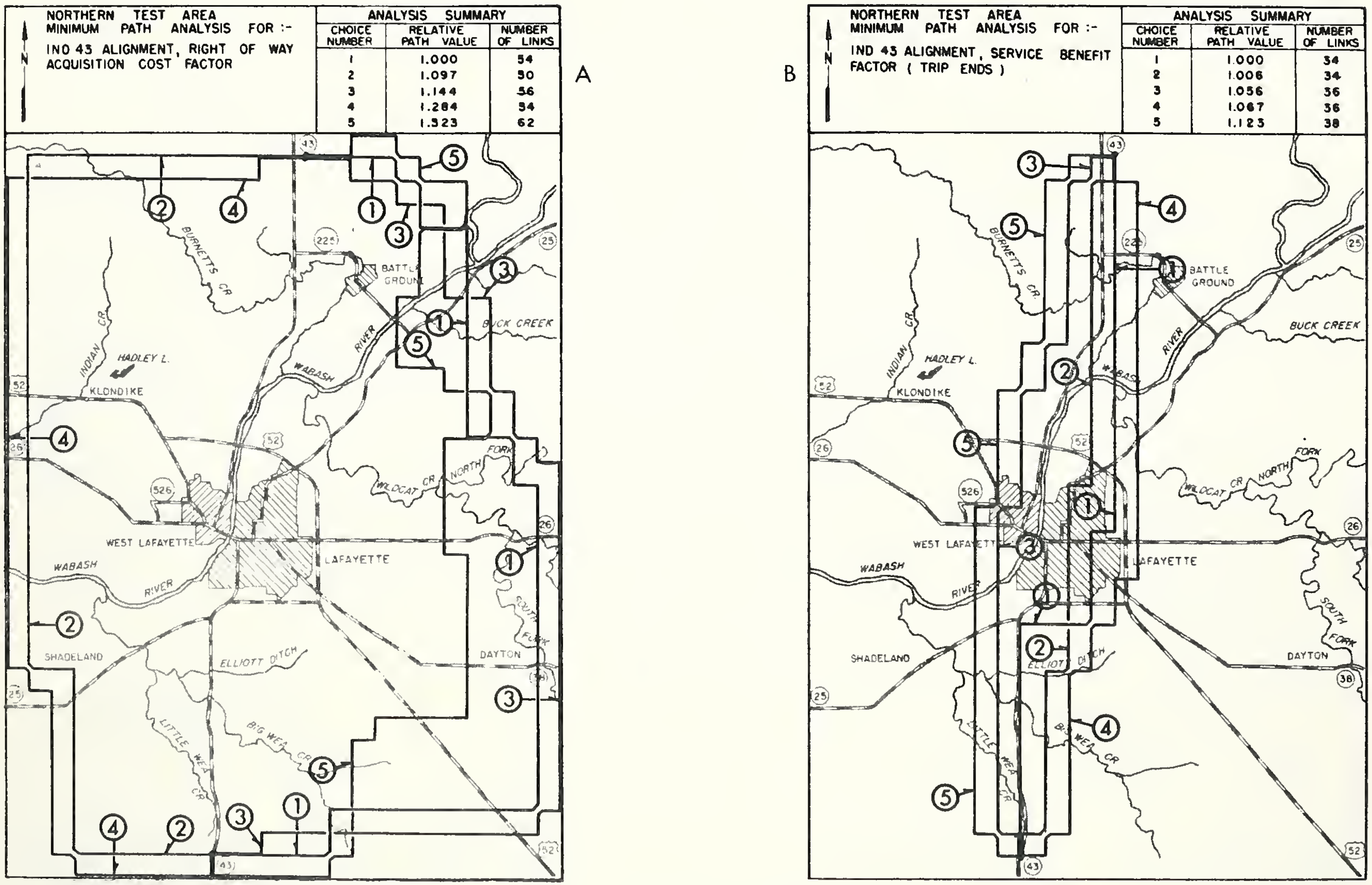
ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	50
2	1.083	48
3	1.182	40
4	1.280	44
5	1.376	48

B

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
IND 43 ALIGNMENT, PAVEMENT CONSTRUCTION COST FACTOR

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	54
2	1.130	40
3	1.304	44
4	1.489	44
5	1.552	40

FIGURE 81. NORTHERN TEST AREA-GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.


A

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
IND 43 ALIGNMENT, RIGHT OF WAY
ACQUISITION COST FACTOR

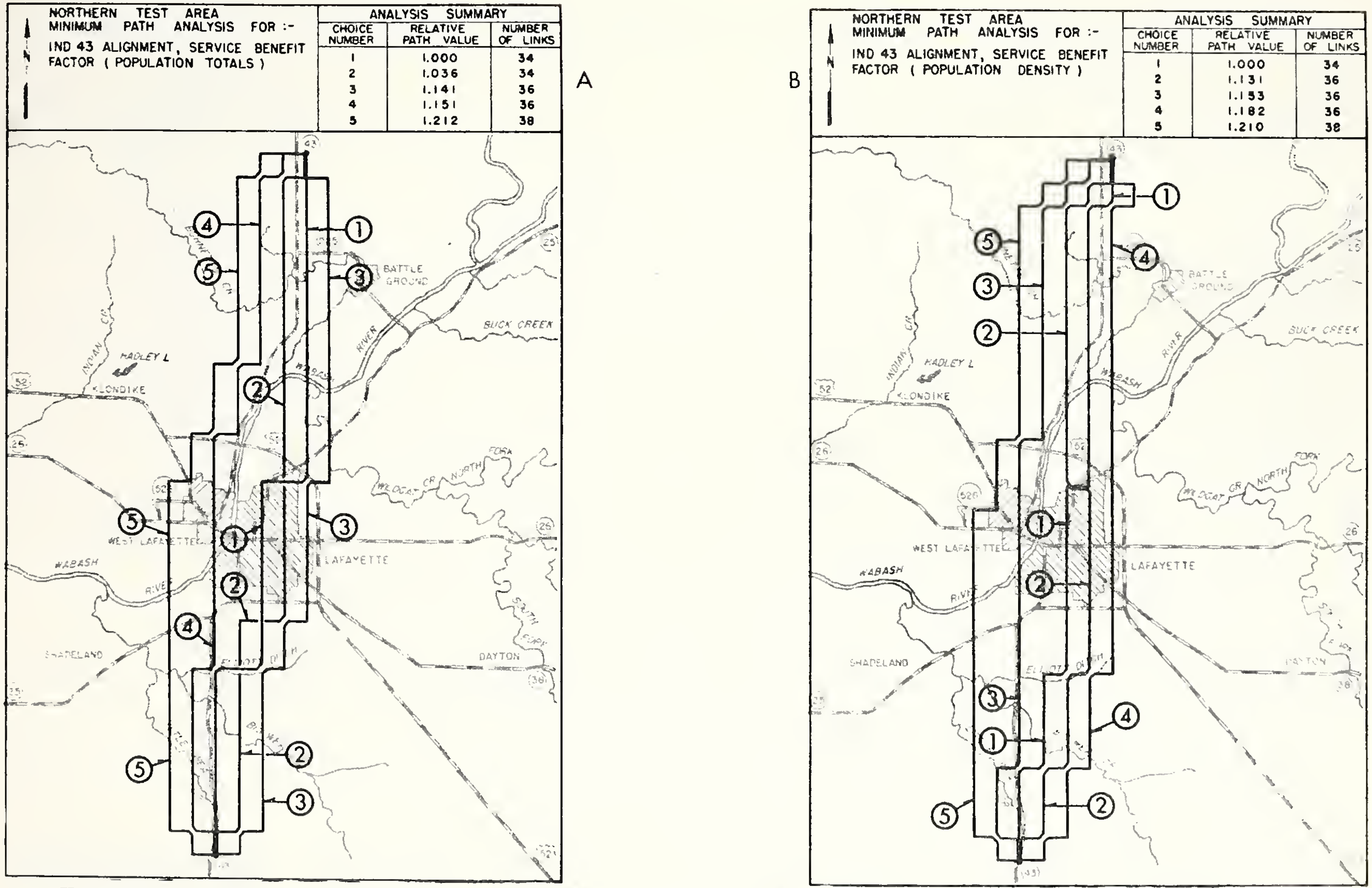
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	54
2	1.097	50
3	1.144	56
4	1.284	54
5	1.323	62

B

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
IND 43 ALIGNMENT, SERVICE BENEFIT
FACTOR (TRIP ENDS)

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	34
2	1.006	34
3	1.056	36
4	1.067	36
5	1.123	38

FIGURE 82. NORTHERN TEST AREA - GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.



A

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
IND 43 ALIGNMENT, SERVICE BENEFIT FACTOR (POPULATION TOTALS)

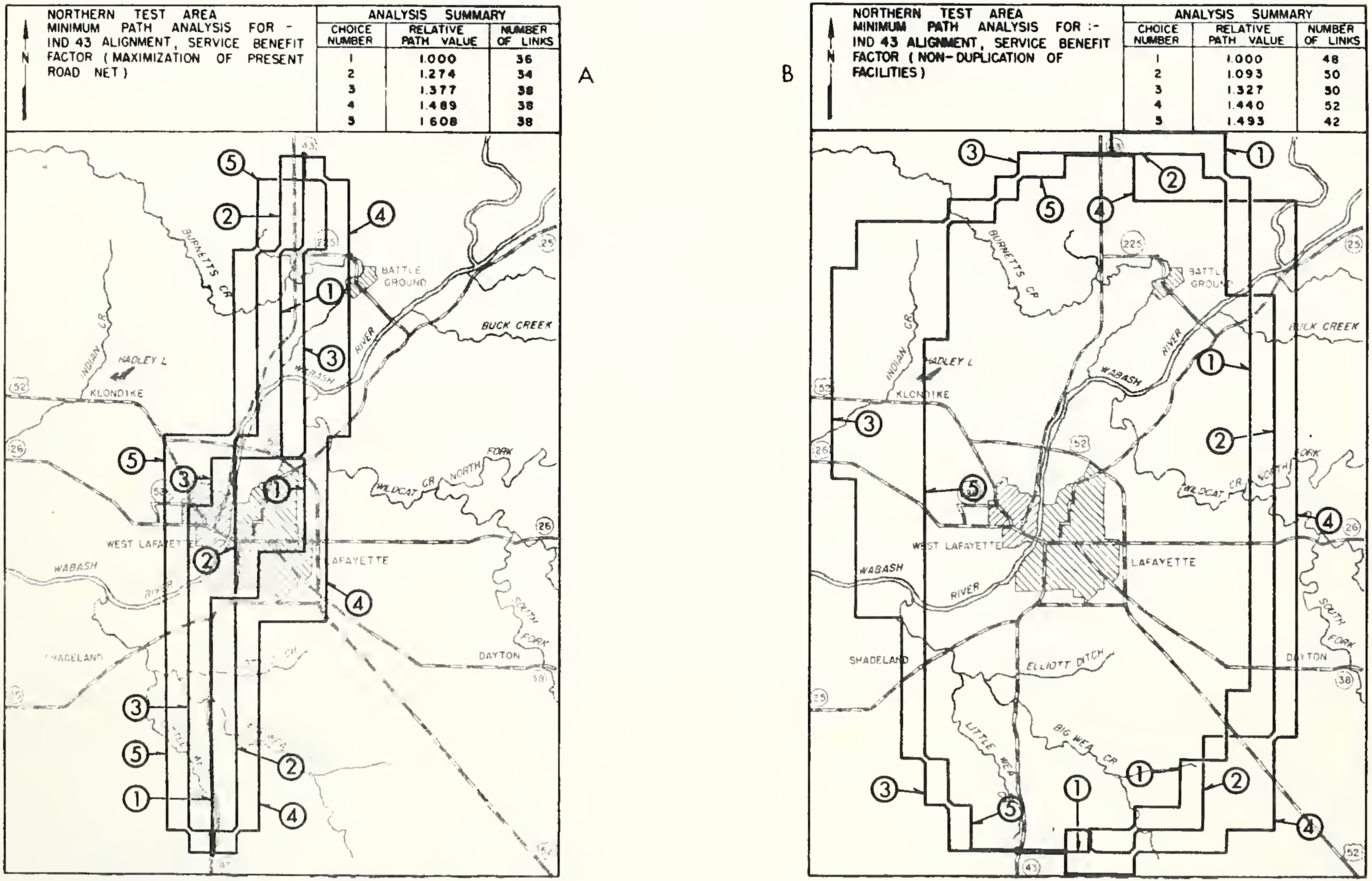
ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	34
2	1.036	34
3	1.141	36
4	1.151	36
5	1.212	38

B

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :-
IND 43 ALIGNMENT, SERVICE BENEFIT FACTOR (POPULATION DENSITY)

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	34
2	1.131	36
3	1.153	36
4	1.182	36
5	1.210	38

FIGURE 83. NORTHERN TEST AREA-GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.



A

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR - IND 43 ALIGNMENT, SERVICE BENEFIT FACTOR (MAXIMIZATION OF PRESENT ROAD NET)

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	36
2	1.274	34
3	1.377	38
4	1.489	38
5	1.608	38

B

NORTHERN TEST AREA
MINIMUM PATH ANALYSIS FOR :- IND 43 ALIGNMENT, SERVICE BENEFIT FACTOR (NON-DUPLICATION OF FACILITIES)

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	48
2	1.093	50
3	1.327	50
4	1.440	52
5	1.493	42

FIGURE 84. NORTHERN TEST AREA - GENERATED ALTERNATIVES FOR SINGLE FACTOR ANALYSES.

Figure 81-B shows the alternatives generated to minimize the pavement construction cost factor. Once again the strong attraction of the granular terrace and outwash plain soils is evident. Only the fourth and fifth choices cross long sections of other types of soils.

The analysis of right of way acquisition costs showed a marked avoidance of populated land. As shown in Figure 82-A, the generated alternatives are divided between an eastern and a western route. Choices one, three, and five favor an eastern route, while choices two and four follow a western route. Many portions of these choices move as far from the Lafayette-West Lafayette metropolitan area as is possible within the limits of the study area.

Analyses of possible service benefits, as measured by population totals, population densities, trip end values, or by maximization of the present road network are shown in Figures 82-B, 83-A, 83-B, and 84-A. These four analyses yield very consistent results with the generated alternatives passing directly through the Lafayette-West Lafayette metropolitan area. Few important differences can be distinguished except that the road net data once again causes the first choice to move closer to the present US 52 bypass. The road net analysis again yields the sharpest optimum of the four analyses. Analysis of the non-duplication of facilities measure of the service benefit factor was also undertaken. Figure 84-B shows the results. Choices one, two, and four favor an eastern route while choices three and five follow a western route. All routes tend to avoid heavily populated areas.

Generation of Multiple Factor Alternatives

The number of different multiple factor analyses totaled 42, split equally between the US 52 route and the State Road 43 route. These analyses can be classified into four categories of differing complexities, as shown in Table 18.

The simplest combined factor analyses involve only two factors. Studies of the earthwork cost and pavement construction cost factors allow the engineer to investigate the route independent construction costs. Three factor analyses, which include the earthwork cost, the pavement construction cost, and the right of way acquisition cost factors, allow the engineer to study the overall facility costs. Four factor analyses include at least one measure of the service benefit factor, which serves to temper the cost considerations. Five factor analyses include two measures of the service benefit factor and the three route independent cost factors.

Results of Analyses for the US 52 Route

When the two factors of earthwork cost and pavement construction cost were combined equally the generated alternatives continued to reflect the distribution of the granular soils shown in Figure 30 (page 111). In Figure 85-A, the first and third choices follow Wildcat Creek while the other alternatives follow the outwash south and west of Lafayette to form a western route. If either factor is emphasized, the resulting choices tend to closely resemble the alternatives found for that factor independently.

As shown in Figure 85-B, when the three factors of earthwork cost, pavement construction cost and right of way acquisition cost are combined

TABLE 18

NORTHERN TEST AREA

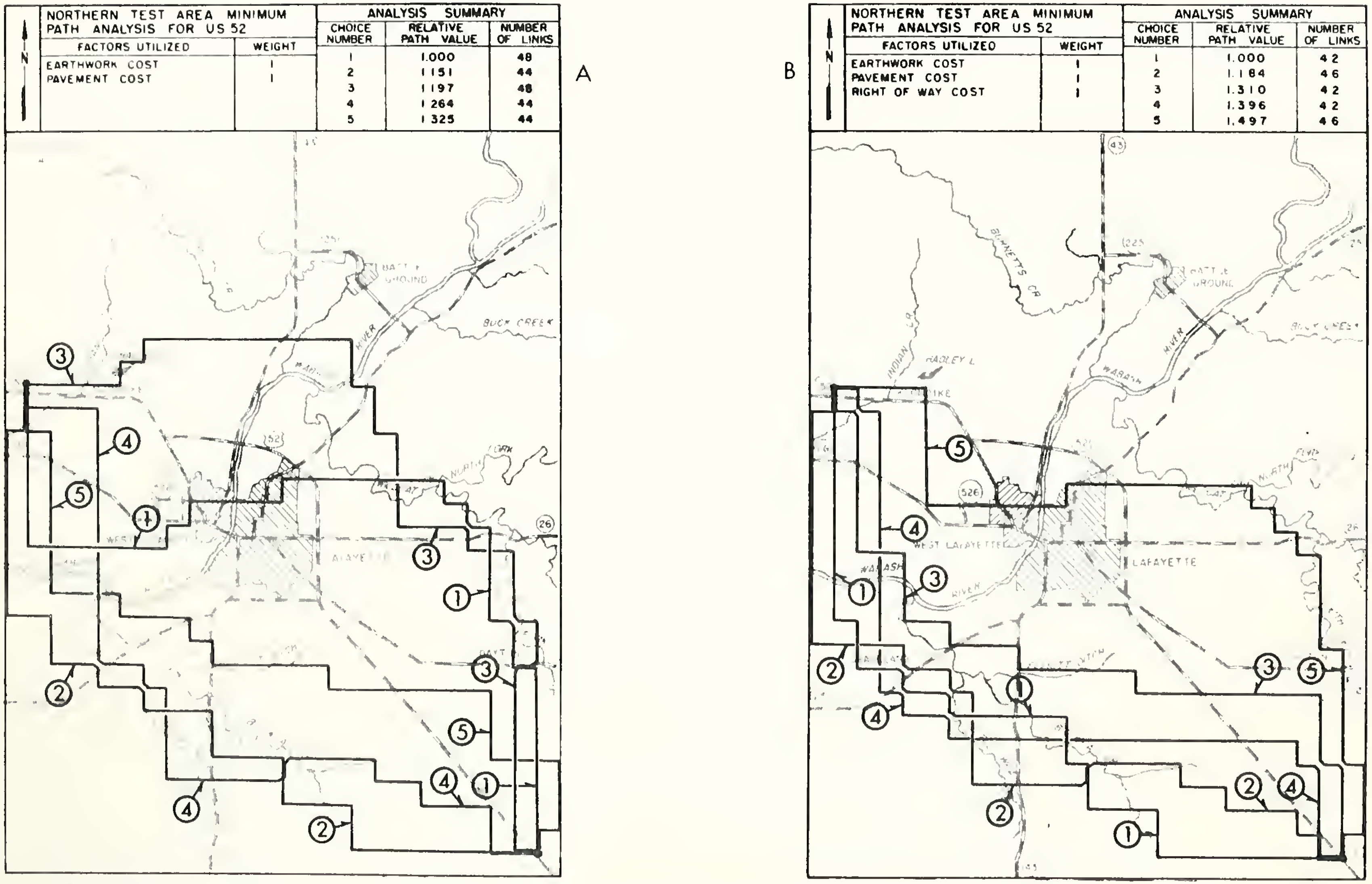
MULTIPLE FACTOR ANALYSES

Category of Analysis	Factor Weights Used in Each Analysis*				
	Earthwork Cost	Pavement Cost	Right of Way Cost	Service Benefits**	
				Trip Ends	Non-duplication of facilities
Two Factor Analyses					
Trial (a)	1	1			
Trial (b)	1	2			
Trial (c)	2	1			
Three Factor Analyses					
Trial (d)	1	1	1		
Trial (e)	1	1	2		
Trial (f)	1	2	1		
Trial (g)	2	1	1		
Four Factor Analyses					
Trial (h)	1	1	1	1	
Trial (i)	2	1	1	1	
Trial (j)	1	2	1	1	
Trial (k)	1	1	2	1	
Trial (ℓ)	1	1	1	2	
Trial (m)	2	2	1	1	
Trial (n)	1	1	4	1	
Trial (o)	2	2	4	1	
Trial (p)	1	1	2	4	
Trial (q)	1	1	1	4	
Five Factor Analyses					
Trial (r)	1	1	1	1	1
Trial (s)	1	1	1	1	2
Trial (t)	1	1	1	4	1
Trial (u)	2	2	4	1	1

---

*Each analysis was performed twice; once for the US 52 Route and once for the State Road 43 Route.

**One special four factor analysis utilizing maximization of the present road network as the only service benefit measure was performed for the US 52 route.



A

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	48
2	1.151	44
3	1.197	48
4	1.264	44
5	1.325	44

B

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1

ANALYSIS SUMMARY

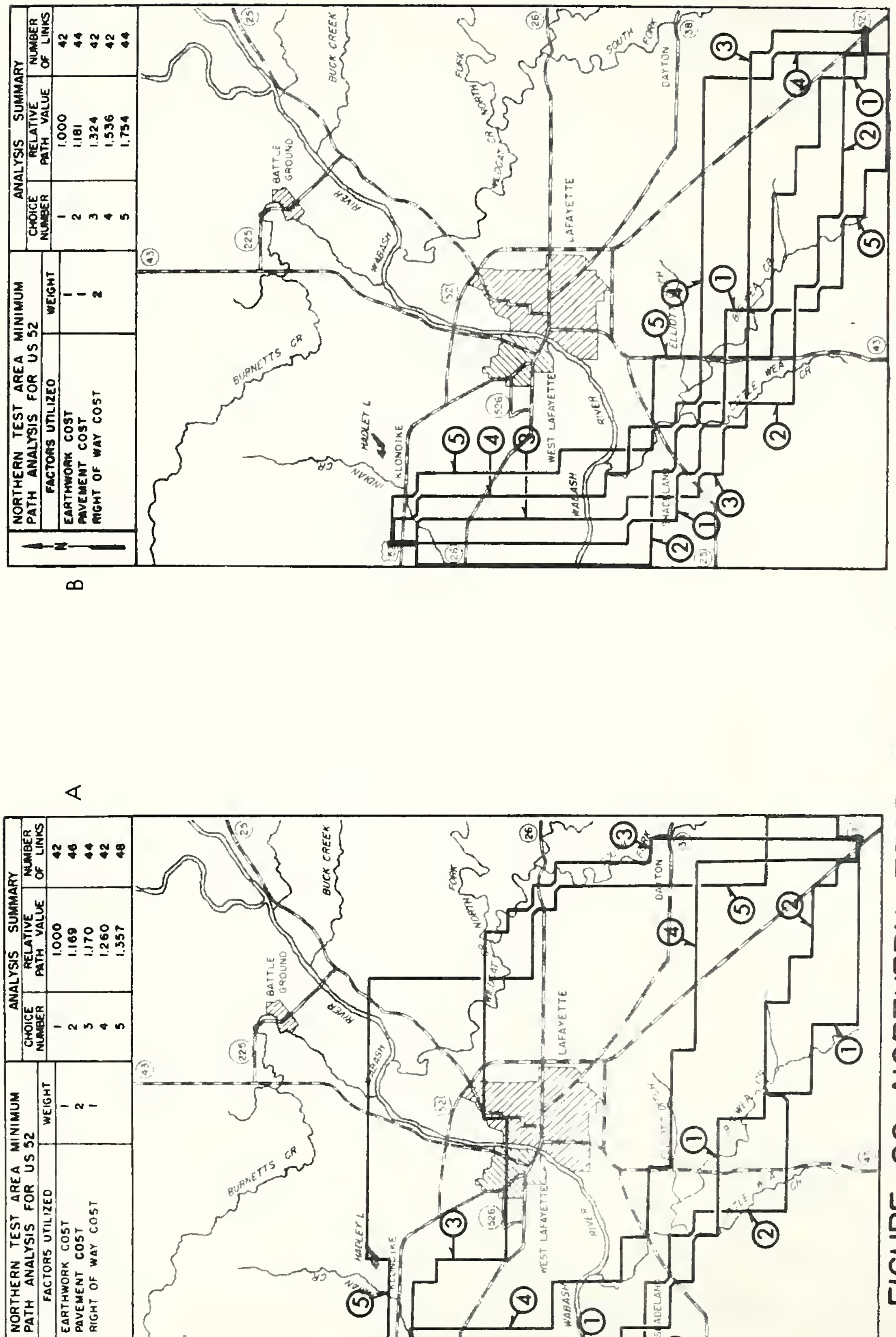
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.184	46
3	1.310	42
4	1.396	42
5	1.497	46

FIGURE 85. NORTHERN TEST AREA-GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.

equally the western bypass is the best alternative. Not until the fifth choice is reached, costing 150 percent of the first choice, does an eastern route emerge following Wildcat Creek and close to the north edge of West Lafayette. If the pavement construction cost factor is given precedence then the alternatives shown in Figure 86-A are generated. Choices one, two, and four follow the western route, while choices three and five follow the Wildcat Creek and Wabash Valley outwash deposits. If the right of way acquisition cost factor is given precedence Figure 86-B reuslts. All choices follow a western route with a sharply defined optimum.

Figures 87-A and 87-B show that slightly different alternatives can be obtained through the use of different service benefit measures. When the present road network is maximized the first choice follows an eastern route (Figure 87-A). However the second choice, following a western route, differs from this first choice by only two percent and the third choice by about ten percent; so that for all practical purposes these alternatives cannot be greatly different in terms of their overall, cost-benefit values. In contrast, when trip end values are used as a service benefit measure all early choices follow a western route (Figure 87-B). Only the fifth choice, exceeding the first choice by about 16 percent, follows an eastern route. The trip end values are believed the best measure for the service benefit factor and were accordingly used extensively in the following four and five factor studies.

Interactions become apparent when the relative importance of the various factors is adjusted. If either the earthwork costs factor or the right of way acquisition costs factor is given added weight (See



A

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52	
FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	2
RIGHT OF WAY COST	1

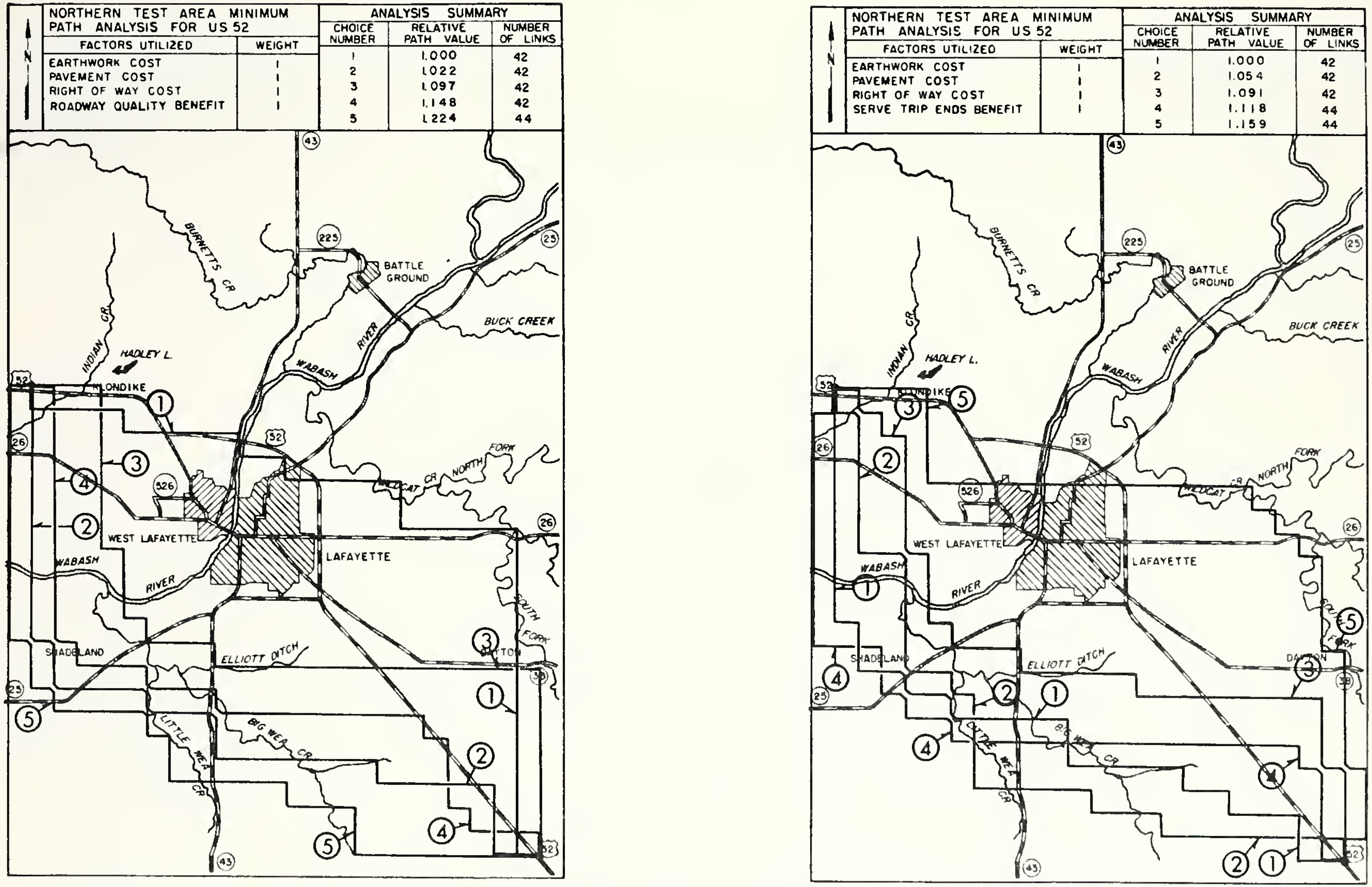
ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.169	46
3	1.170	44
4	1.260	42
5	1.357	48

B

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52	
FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	2

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.181	44
3	1.324	42
4	1.536	42
5	1.754	44

FIGURE 86. NORTHERN TEST AREA - GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.



NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1
ROADWAY QUALITY BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.022	42
3	1.097	42
4	1.148	42
5	1.224	44

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1
SERVE TRIP ENDS BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.054	42
3	1.091	42
4	1.118	44
5	1.159	44

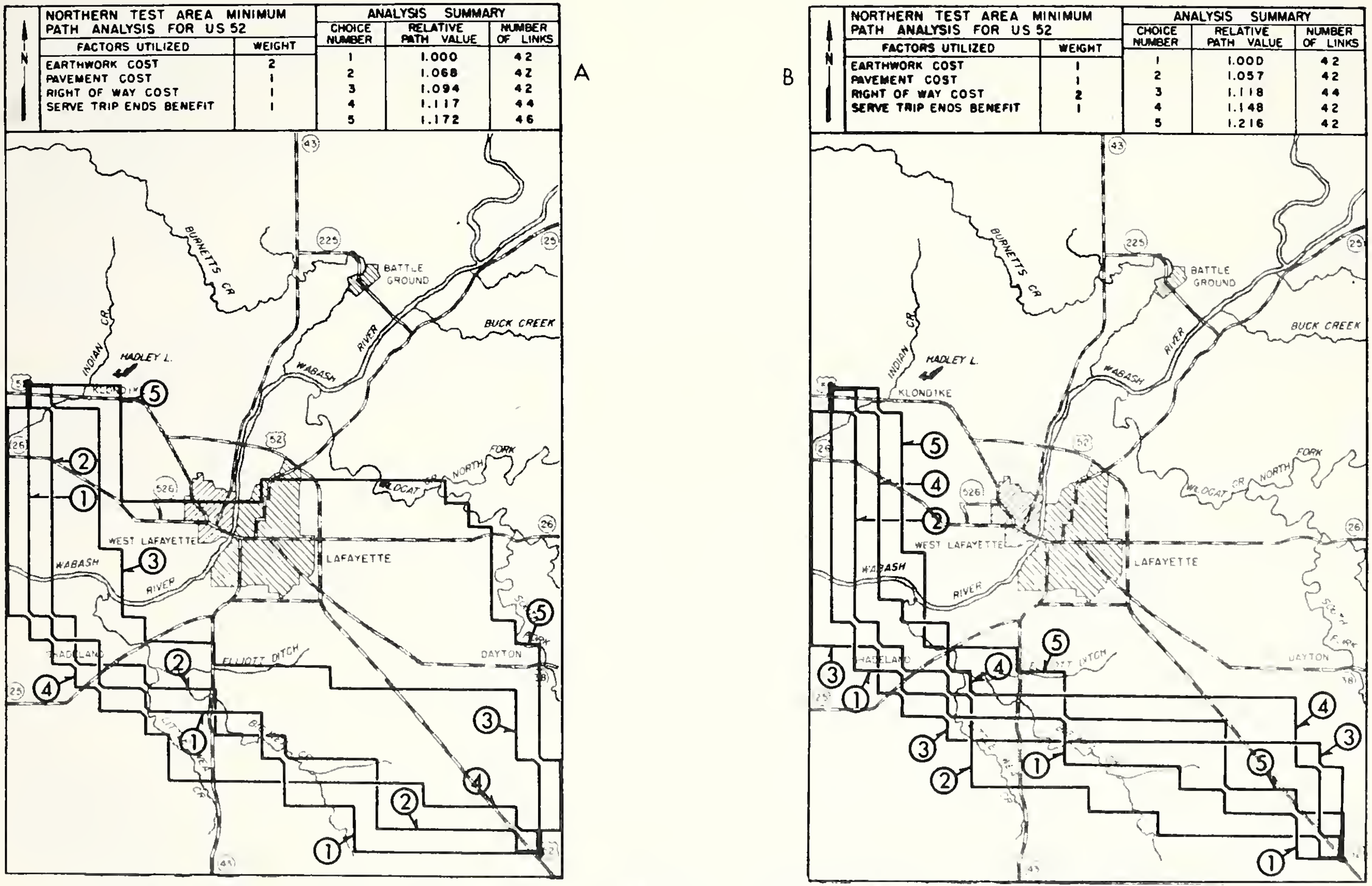
FIGURE 87. NORTHERN TEST AREA - GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.

Figure 88-A and 88-B) then a western route is favored. As shown in Figure 89-A, giving the pavement construction cost factor added importance causes an eastern route to become almost as attractive as the western route. This condition remains essentially constant even if the earthwork construction costs are also raised in importance, as shown in Figure 89-B.

In order to determine what importance had to be attached to the service benefit before an eastern route became attractive, several analyses were made with the trip ends measure of the service benefit factor raised to strong precedence. The results are shown in Figure 90-A. The eastern route never became preeminent under these conditions, while raising the importance of the right of way acquisition cost factor quickly negated any tendency to raise the relative worth of the eastern route (see Figure 90-B).

A western route is favored a five factor study with all factors given equal weights; only the fifth choice selects an eastern route. When the trip ends measure of the service benefit factor is raised to strong preeminence the western route remains popular. However the second alternative now goes into the heart of the Lafayette metropolitan area, while the fourth choice follows a more easterly route.

Figure 91-A shows the alternatives generated for what the author believes is the most realistic weighting of the five factors for the northern test area. This weighting of the five factors shows the western route to be preferred. Out of the total location valuation scheme, 80 percent is given to first costs and 20 percent to benefits. The costs are divided into two parts; right of way acquisition costs equalling 40 percent and construction costs equalling 40 percent. Construction costs



A

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	2
PAVEMENT COST	1
RIGHT OF WAY COST	1
SERVE TRIP ENDS BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.068	42
3	1.094	42
4	1.117	44
5	1.172	46

B

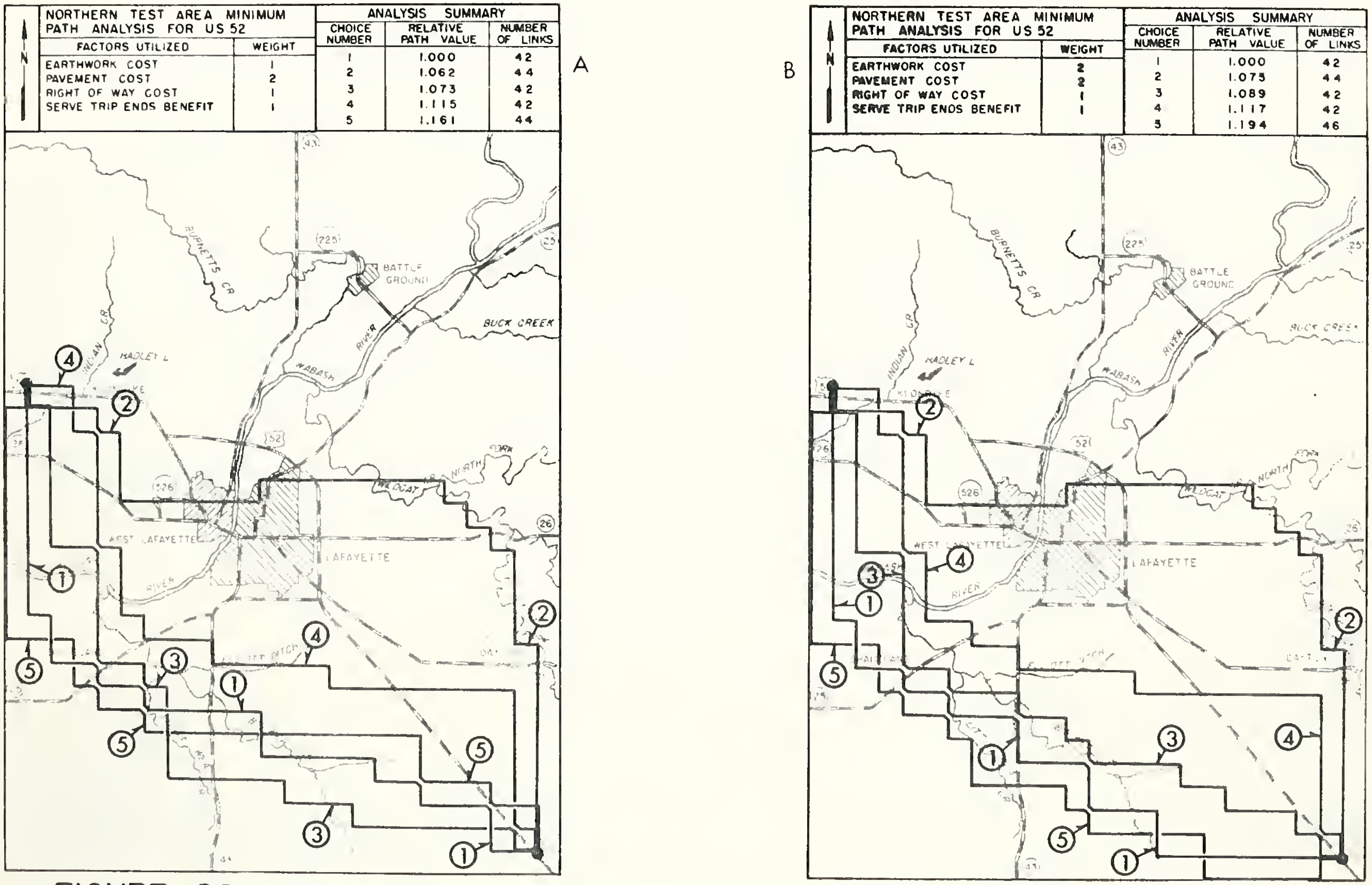
NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	2
SERVE TRIP ENDS BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.057	42
3	1.118	44
4	1.148	42
5	1.216	42

FIGURE 88. NORTHERN TEST AREA-GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.



A

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	2
RIGHT OF WAY COST	1
SERVE TRIP ENDS BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.062	44
3	1.073	42
4	1.115	42
5	1.161	44

B

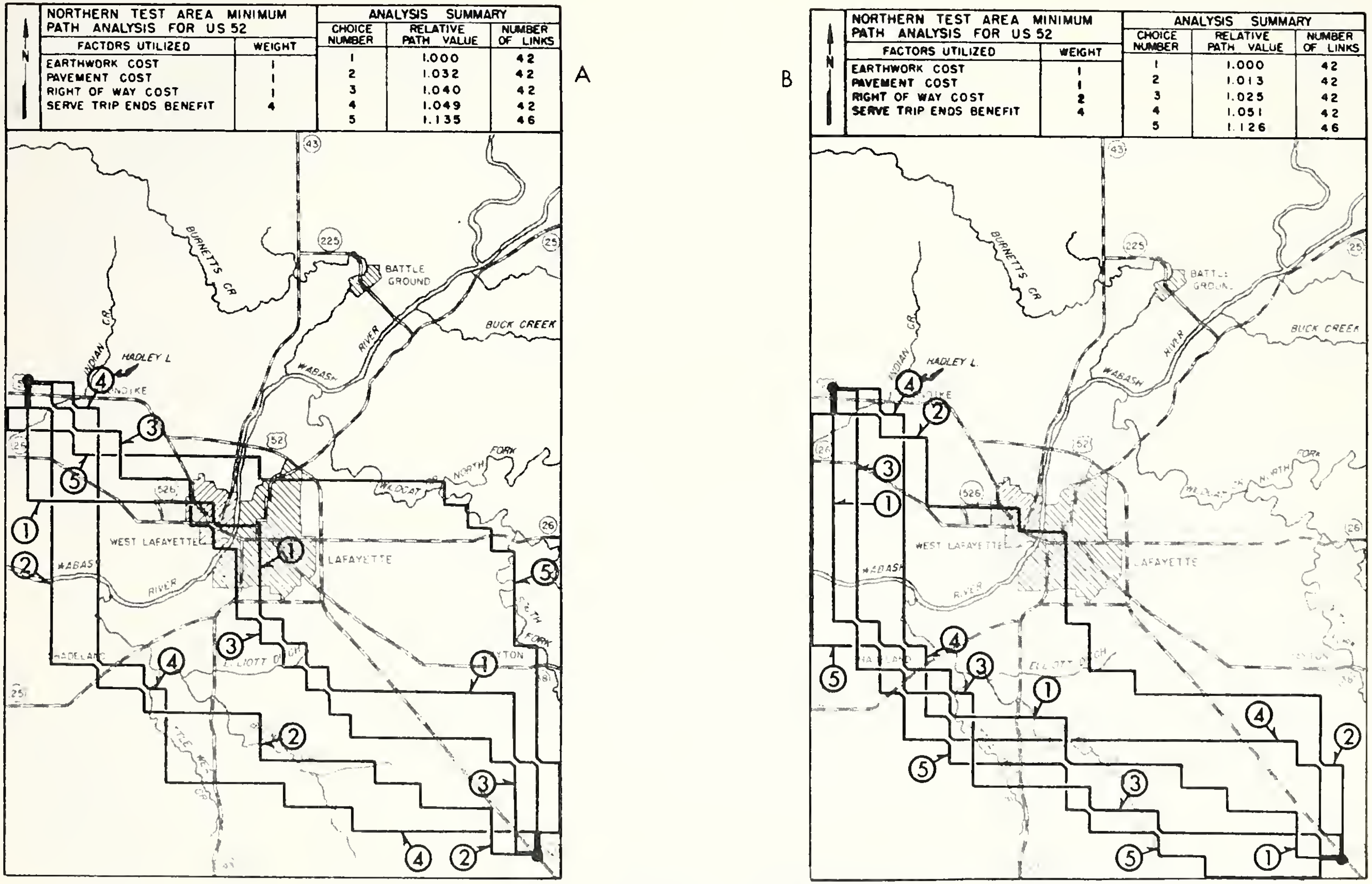
NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	2
PAVEMENT COST	2
RIGHT OF WAY COST	1
SERVE TRIP ENDS BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.075	44
3	1.089	42
4	1.117	42
5	1.194	46

FIGURE 89. NORTHERN TEST AREA-GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.



A

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52 FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1
SERVE TRIP ENDS BENEFIT	4

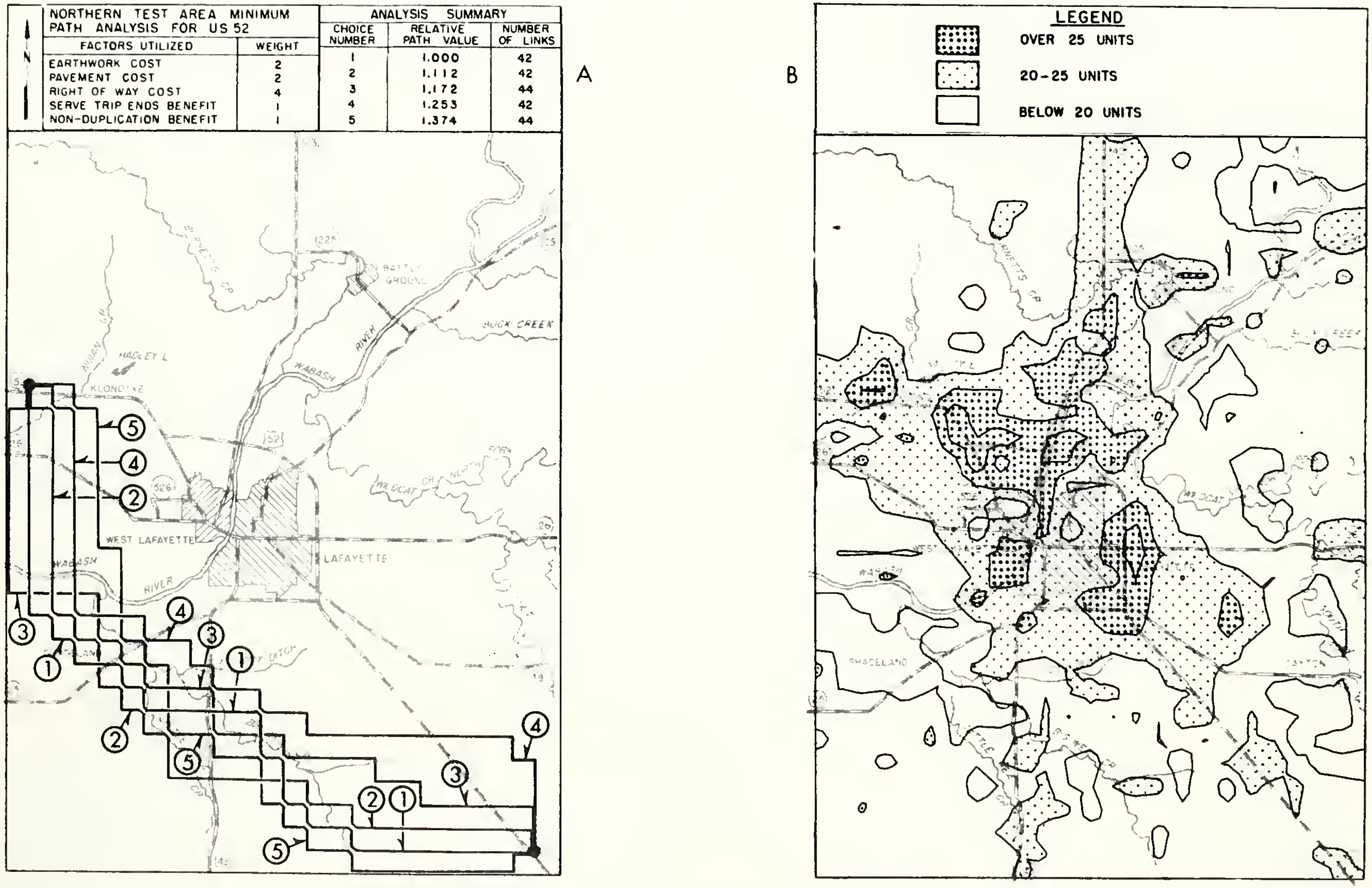
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.032	42
3	1.040	42
4	1.049	42
5	1.135	46

B

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52 FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	2
SERVE TRIP ENDS BENEFIT	4

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.013	42
3	1.025	42
4	1.051	42
5	1.126	46

FIGURE 90. NORTHERN TEST AREA - GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.



NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR US 52	
FACTORS UTILIZED	WEIGHT
EARTHWORK COST	2
PAVEMENT COST	2
RIGHT OF WAY COST	4
SERVE TRIP ENDS BENEFIT	1
NON-DUPLICATION BENEFIT	1

ANALYSIS SUMMARY		
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	42
2	1.112	42
3	1.172	44
4	1.253	42
5	1.374	44

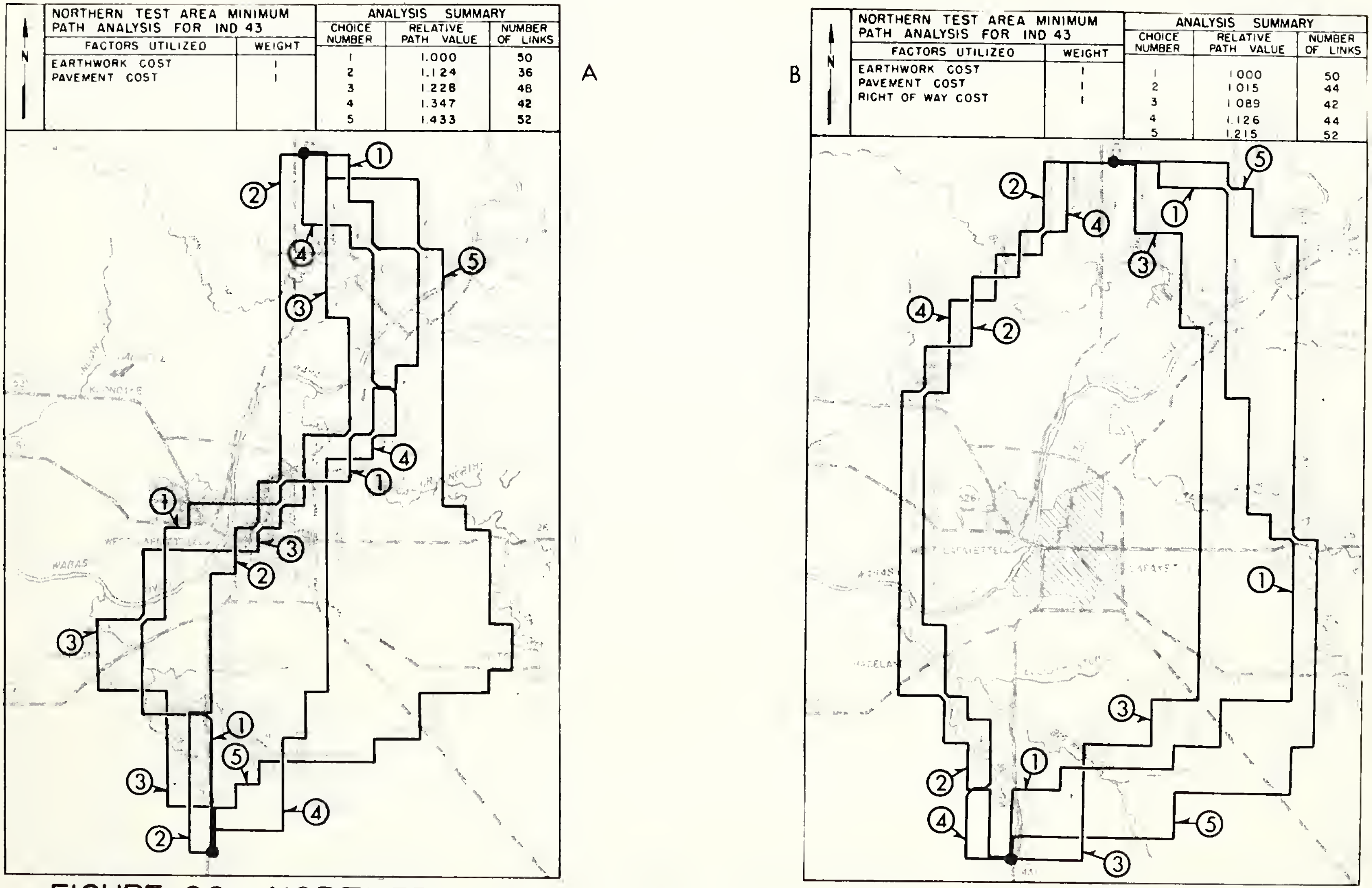
FIGURE 91. NORTHERN TEST AREA - FINAL GENERATED MULTIPLE FACTOR ALTERNATIVES AND MAP OF CORRESPONDING UTILITY SURFACE.

are equally divided into earthwork costs (20%) and pavement construction costs (20%). The benefit measure is equally divided between serving travel demand as measured by trip end data (10%), and non-duplication of facilities (10%). Figure 91-B shows a computer generated contour map of this utility surface.

Results of Analyses for the State Road 43 Route

Figure 92-A shows the alternatives generated when the factors of earthwork cost and pavement construction cost are weighted equally. The distribution of granular soils continues to affect the results. The first choice follows Wea Creek to the Wabash valley, then travels along the terraces until east of Battle Ground before finally swinging north and west to the destination. The second choice quite closely follows the present State Road 43 alignment. The third choice is similar to the first although it is not as long since it passes west of Battle Ground. The fourth choice passes east of Lafayette then is intermediate to choices one and three. The fifth choice travels far to the east and follows Wildcat Creek.

Figure 92-B shows the alternatives generated when the right of way acquisition cost factor is added to the first two factors. The generated routes now tend to avoid populated areas. Choices one, three, and five favour eastern routes. Each defines a unique alternative however. The third choice differs from the first choice by less than nine percent; however the fifth choice is over twenty percent greater than the first choice. Choices two and four define a single western route that follows Wea Creek to the Wabash valley then trends northeast to the destination.



A

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR IND 43

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	50
2	1.124	36
3	1.228	48
4	1.347	42
5	1.433	52

B

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR IND 43

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	1

ANALYSIS SUMMARY

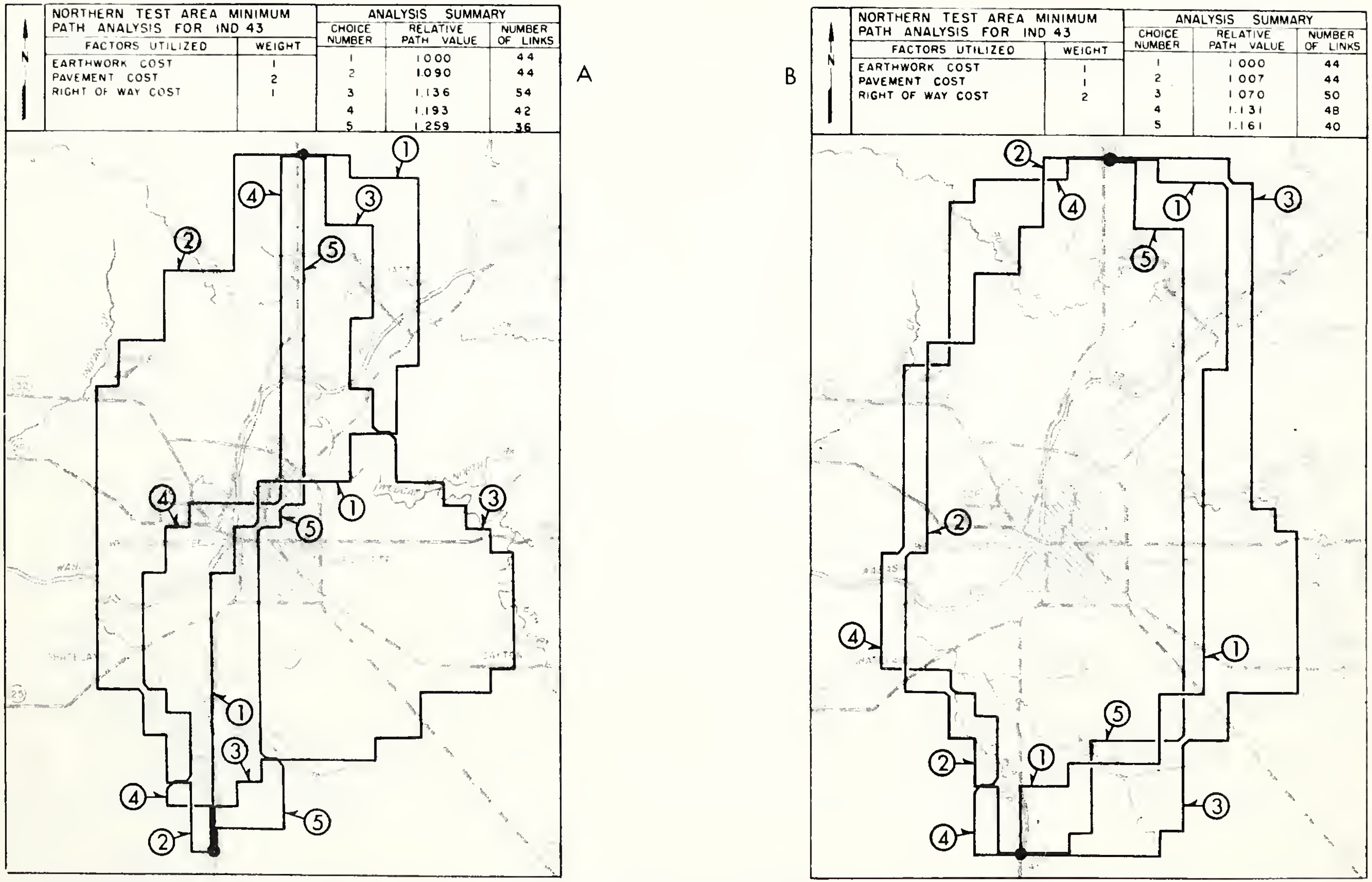
CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	50
2	1.015	44
3	1.089	42
4	1.126	44
5	1.215	52

FIGURE 92. NORTHERN TEST AREA-GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.

If the relative importance of the three factors is changed, different alternatives are generated. Figure 93-A shows the results generated when the pavement construction cost factor predominates, Figure 93-B shows the generated alternatives when the right of way acquisition cost factor predominates. In Figure 93-A all alternatives tend to follow granular outwash soils as much as possible. Several alternatives pass through the populated portions of Lafayette or West Lafayette while following the terrace deposits along the Wabash. Other alternatives follow Wildcat Creek or Wea Creek. When the right of way cost factor predominates, as shown in Figure 93-B, alternatives are divided between an eastern and a western corridor. These are similar to the routes shown in Figure 92-B, however the alternative corridors are now more sharply defined than in the earlier analysis. This is especially true for the eastern corridor.

Figure 94-A shows the alternatives generated for four equally weighted factors; earthwork cost, pavement construction cost, right of way acquisition cost and the service benefit factor, measured by the trip ends distribution. The first three choices all pass through the center of the Lafayette metropolitan area. The second choice lies to the east of the first and third choices which quite closely follow the present State Road 43 alignment over most of its length. The fourth choice defined an eastern route, while the fifth choice defines a western bypass.

If the importance of the service benefit factor is raised, the choices are generated as shown in Figure 94-B. All five choices define a series of closely spaced north-south trending alternatives. All choices are about equal; the fifth choice is only 108 percent of the first choice.



A

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR IND 43

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	2
RIGHT OF WAY COST	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	44
2	1.090	44
3	1.136	54
4	1.193	42
5	1.259	36

B

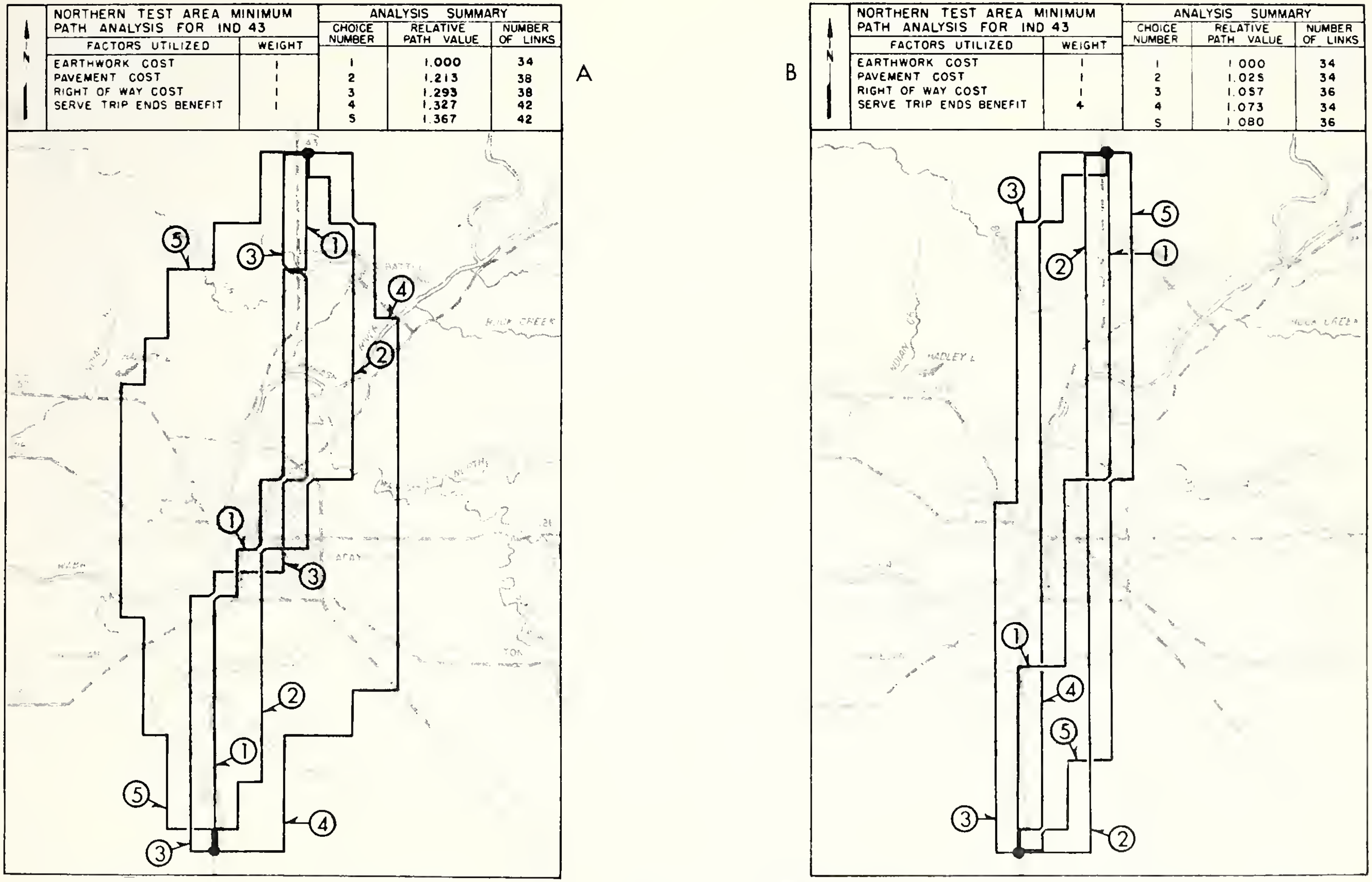
NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR IND 43

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	1
PAVEMENT COST	1
RIGHT OF WAY COST	2

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	44
2	1.007	44
3	1.070	50
4	1.131	48
5	1.161	40

FIGURE 93. NORTHERN TEST AREA - GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.



A

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR IND 43		ANALYSIS SUMMARY		
FACTORS UTILIZED	WEIGHT	CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
EARTHWORK COST	1	1	1.000	34
PAVEMENT COST	1	2	1.213	38
RIGHT OF WAY COST	1	3	1.293	38
SERVE TRIP ENDS BENEFIT	1	4	1.327	42
		5	1.367	42

B

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR IND 43		ANALYSIS SUMMARY		
FACTORS UTILIZED	WEIGHT	CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
EARTHWORK COST	1	1	1.000	34
PAVEMENT COST	1	2	1.025	34
RIGHT OF WAY COST	1	3	1.057	36
SERVE TRIP ENDS BENEFIT	4	4	1.073	34
		5	1.080	36

FIGURE 94. NORTHERN TEST AREA - GENERATED ALTERNATIVES FOR MULTIPLE FACTOR ANALYSES.

Although not shown, increasing the importance of the right of way acquisition cost factor causes the generated alternatives to move out from the densely populated areas.

Figure 95 shows the alternatives generated for five factors weighted in what is believed to be a realistic manner for the conditions prevailing in the northern test area. The factors and weights are:- earthwork cost (20%), pavement construction cost (20%), right of way acquisition cost (40%), trip end service (10%), and non-duplication of facilities (10%). This is the same weighting as shown for the US 52 alignment in Figure 91-A.

The first, third, and fifth choices define eastern routes; the second and fourth choices, western routes. Each choice defines a distinct alternative. The second and third choices are considerably shorter than the other alternatives. The fifth choice exceeds the cost of the first choice by over twenty-one percent.

Evaluation of Alternatives

The final analyses for both the US 52 and State Road 43 routes are shown in Figures 91-A and 95. Figure 91-B shows the utility surface analyzed for both these routes. The generated alternatives for each route were evaluated to determine if re-ordering the alternatives was necessary to reflect route dependent factors.

The five alternatives generated for the US 52 route (see Figure 91-A) closely parallel one another. Except in the southeast where choices three and four diverge from the others, a single corridor is identified. The alternatives are approximately the same length; three are 42 links long and two are 44 links long. Thus under these circumstances no

NORTHERN TEST AREA MINIMUM PATH ANALYSIS FOR IND 43

FACTORS UTILIZED	WEIGHT
EARTHWORK COST	2
PAVEMENT COST	2
RIGHT OF WAY COST	4
SERVE TRIP ENDS BENEFIT	1
NON-DUPLICATION BENEFIT	1

ANALYSIS SUMMARY

CHOICE NUMBER	RELATIVE PATH VALUE	NUMBER OF LINKS
1	1.000	50
2	1.055	44
3	1.143	42
4	1.172	50
5	1.215	54

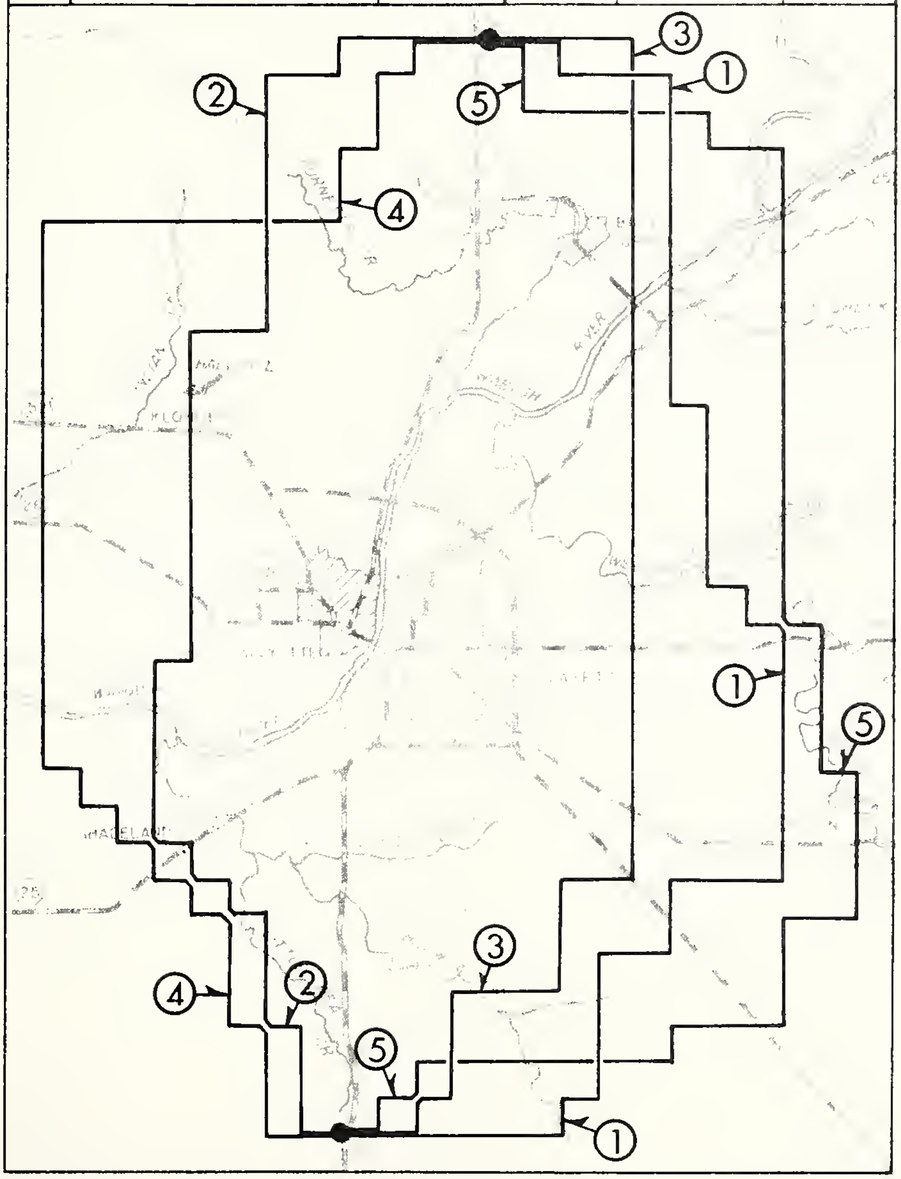


FIGURE 95. NORTHERN TEST AREA - FINAL GENERATED MULTIPLE FACTOR ALTERNATIVES.

re-ordering of alternatives is believed necessary. More detailed analysis should be directed to the corridor containing all these alternatives.

The five alternatives generated for the State Road 43 route shown in Figure 95 suggest several distinctly different choices. The lengths range from a low of 42 links for choice number three to a high of 54 links for choice number five. Some re-ordering is thus believed desirable. The second choice cost exceeds the first choice cost by 5.5 percent yet its length is 12 percent less (44 links to 50 links). Similarly the third choice cost is 14.3 percent more than the first choice, yet it is 16 percent shorter (42 links to 50 links). The lengths of the fourth and fifth choices equal or exceed the length of the first choice.

As discussed in Chapter V, shorter routes are generally more desirable than longer ones. The relative importance of distance and first cost depends on the relative importance of the route-dependent and route-independent factors. If they are assumed to have equal importance the State Road 43 alternatives should be re-ordered as follows:- (1) choice two, (2) choice three, (3) choice one, (4) choice four, and (5) choice five. Different ordering would result if different relative importance was attached to the two classes of factors.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This project undertook an evaluation of new regional highway location procedures; in particular, the role of the digital computer in the preliminary phases of the design process. Based on the results obtained at two test areas in Indiana it is concluded that:

1. Computer-aided regional highway location procedures can assist design engineers in generating and evaluating alternative locations.
2. The Generalized Computer-Aided Route Selection (GCARS) System developed in this project forms a prototype system which includes three basic subdivisions that must exist in all similar systems. The subdivisions are defined as "activities" and are called (a) the data preparation activity, (b) the search activity, and (c) the selection activity. These activities require decisions from the design engineer; the computer is programmed to store, analyze, and retrieve data so as to enhance the decision-making capabilities of the design engineer. Therefore, the system includes two partners, the design engineer and the computer, and effective and convenient man-to-machine and machine-to-man communications must be provided.

3. There are two classes of highway location factors; those that can be studied without first defining a route, and those that can only be studied with reference to defined alternatives. The former are termed "route-independent factors;" the latter, "route dependent factors." Route-independent factors can be used to generate a preliminary set of alternative locations, which can be modified with reference to the route-dependent factors.
4. In regional highway location studies there are four important route-independent factors: (1) an earthwork cost factor; (2) a pavement construction cost factor; (3) a right of way acquisition cost factor; and (4) a service benefit factor. Different factors should be studied in connection with other forms of transportation. Information on each factor can be obtained from a "measure" for the factor. Measures must be progressively transformed to "values" and "utilities". Values define the factor in terms of costs or benefits; benefits being considered the inverse of costs. Utilities are standardized and transformed values so that minimum path analysis may be performed.
5. Topographic maps form a suitable measure of the earthwork cost factor. Engineering soils maps can be used as measures of the pavement construction cost factor. Land use data obtained by interpretation of aerial photographs is an adequate measure of the right of way acquisition cost. Population or trip end data and the distribution of highway facilities can be used as measures of the service benefit factor.

6. Several numerical surface analysis procedures have important applications in the GCARS System. Vector analysis procedures are useful in classifying terrain and thus help determine suitable sampling procedures for topographic data. Trend surface analysis is an important method of checking sampled values for accuracy and lack of bias. Trend surface analysis also has a special use in transforming elevation data to earthwork cost values, through the use of residuals. Surface comparison procedures give objective measures of similarity between different values of the same or different factors. Weighted moving average procedures estimate gridded values from irregularly sampled data. These can define value and utility surfaces and are important in the development of utility networks.
7. Computer generated graphic displays are an extremely important form of machine-to-man communication. Contour maps produced on the printer as part of the program output are the cheapest, fastest, and most convenient form of graphical output developed so far. Maps produced on special plotters are useful for more careful study of critical situations and for the development of final report illustrations.
8. Utility networks are defined from a series of gridded utility surface quantities. The grid spacing must be appropriate to the level of the analysis within the highway planning hierarchy; generally this means that the grid spacing should not exceed the desired width of the alternative Bands, Corridors, or Routes being generated.

9. Generation of alternatives in terms of single route-independent factors is accomplished by constructing a unique utility surface for each factor, determining a suitable utility network, and repeatedly analyzing it by minimum path analysis procedures.
10. Generation of multiple factor alternatives is possible if a combined utility surface is constructed by summing the individual utility surfaces for each factor, determining a suitable utility network, and repeatedly analyzing it by minimum path analysis procedures.
11. Factors can be combined in varying proportions by multiplying the utilities of the factors by appropriate weighting functions and then summing the products. Repeated analysis of groups of factors combined in different relative weights allows the design engineer to identify and evaluate interactions between and among the various factors.
12. The prototype GCARS System performs minimum path analysis on utility networks which can be stored and analyzed by the computer in their entireties. Thus even with comparatively large computer systems, such as the CDC 6500 configuration installed at Purdue University, the maximum size of the utility networks that can be studied is approximately 1200 nodes and 4800 links, corresponding to a 30 by 40 utility matrix. Analysis of larger networks would require their decomposition into sub-networks. Implementation of network decomposition procedures into the GCARS System requires further study.

13. The alternatives generated in response to the route-independent factors by the GCARS System can be evaluated with respect to appropriate route-dependent factors by the design engineer. Re-ordering of the alternatives to reflect both classes of factors results in the identification of the relative advantages of each alternative.

Recommendations

During the evaluation and development of the prototype GCARS System, a number of potential applications and research problems become apparent which were beyond the scope of the current project. Accordingly they are included in the following recommendations for further study:

1. A program should be initiated to compare the established data collection and analysis procedures utilized by various highway planning authorities with the data requirements of the GCARS System. Appropriate plans to implement the GCARS System into routine highway planning procedures cannot be developed until such a study is completed.
2. Consideration should be given to "field testing" the GCARS System by applying it to actual regional transportation problems. A variety of problems should be utilized. The use of a GCARS System approach to the analysis of regional transportation plans in developing countries should not be overlooked.
3. Modifications to the prototype GCARS System should be developed to make it more suited to the large volumes of data likely to be encountered in full scale applications. The modifications are needed in the following areas: (a) data storage and handling

procedures; and (b) minimum path analysis of very large networks.

The prototype GCARS System utilizes machine-punched cards for much of the required intermediate data storage. This becomes unwieldy with very large data sets, and thus the system needs to be modified to allow intermediate data storage on magnetic tape or disc packs.

Analysis of large networks requires their decomposition into sub-networks. Such procedures have been developed but further research is required before these can be implemented into the GCARS System analyses.

4. New types of computer-generated graphic displays should be investigated for possible implementation into the GCARS System. Procedures for producing isometric drawings of the value surfaces would be especially desirable. New devices, such as cathode ray tube display units, are constantly being developed and may produce superior displays at lower costs.
5. Studies should be undertaken to determine if several factors can be evaluated directly from aerial photography. The prototype GCARS System used mapped data as measures of the various factors. Many of these maps were originally developed by photointerpretation and/or photogrammetric procedures. Thus direct extraction of the data from photography might prove to be more efficient.
6. Application of the GCARS System should be undertaken in urban areas for which land use data banks have been or are being developed. It appears probable that the system could satisfactorily analyze urban transportation alternatives when such

improved source data are available.

7. A research project should be designed to study the interactions between a GCARS System and land use development and traffic estimation models. A variety of suitable simulation models have been developed by various metropolitan transportation planning agencies. A combined system would allow the GCARS System to generate alternative designs, while the simulation model could test the long term effects of each alternative. Such an approach would allow the design engineers to select the best alternative in terms of both immediate and long term effects.
8. The GCARS System approach should be evaluated for other forms of transportation or for communication networks. Identification and evaluation of suitable factors would be required in each case. However it seems probable that studies of pipelines, electrical transmission lines, railroads, and canals would be of great value.

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VITA

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A. Keith F. Turner was born August 5, 1941 in Edinburgh, Scotland. From 1945 until 1952 his family lived in central and southern England where he began his elementary schooling. In April 1952 the family emigrated to Canada and settled at Cornwall, Ontario, where he completed his elementary and high school education.

Mr. Turner attended Queens University, Kingston, Ontario from 1959 to 1963 where he studied Engineering Geology and obtained a B.Sc. (hons.) degree in May 1963. In September 1963 Mr. Turner entered Columbia University on a Eugene Higgins Fellowship and obtained an M.A. degree in geology, with emphasis on geomorphology and structural geology, in September 1964.

During the summer months of 1962, 1963, and 1964 Mr. Turner worked for the Ontario Department of Highways, Toronto, Ontario. Employed on a variety of problems in aggregate quality control and evaluation, Mr. Turner conducted geologic field work in several areas of Southern Ontario. The summer season of 1964 formed the basis of his Master's thesis which described the glacial sand and gravel deposits north of Toronto.

Mr. Turner entered Purdue University in September 1964. In January 1966 Mr. Turner joined the Testing Laboratories, Department of Public Works, Ottawa, Canada, as Engineering Geologist. In September 1966 he returned to Purdue on an educational leave of absence to complete his research for the Ph.D. degree. In January 1967 Mr. Turner was appointed

Engineering Geologist to the staff of the Atlantic Tidal Power Programming Board, Halifax, Nova Scotia, Canada and has worked at this position on a consulting basis until the present time. In September 1967 Mr. Turner received the Warnock Hersey Canadian Good Roads Association Fellowship to aid in the completion of his research.

Mr. Turner is a member of the Association of Professional Engineers of the Province of Ontario, the Geological Society of America, the Indiana Academy of Science, the Highway Research Board, and is an associate member of Sigma Xi.

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